PB86-161304

Economic Evaluation of Oil Agglomeration for Recovery of Fine Coal Refuse

(U.S.) Tennessee Valley Authority
Muscle Shoals, AL

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Aug 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-161304

EPA/600/7-85/032
August 1985

Economic Evaluation of Oil Agglomeration for Recovery of Fine Coal Refuse

by

L. Larkin and J.D. Maxwell

TVA, Power and Engineering
Division of Energy Demonstrations and Technology
Muscle Shoals, Alabama 35661

EPA Interagency Agreement No. 79-D-X0511

EPA Project Officer: Julian W. Jones

Air and Energy Engineering Research Laboratory
Office of Environmental Engineering and Technology
Research Triangle Park, NC 27711

AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/7-85/032	2.
3. RECIPIENT'S ACCESSION NO. PB86 161304/AS	
4. TITLE AND SUBTITLE Economic Evaluation of Oil Agglomeration for Recovery of Fine Coal Refuse	5. REPORT DATE August 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) L. Larkin and J. D. Maxwell	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Tennessee Valley Authority, Power and Engineering, Division of Energy Demonstration and Technology, Muscle Shoals, Alabama 35661	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. IAG 79-D-X0511
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 1/82 - 2/85
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Julian W. Jones, Mail Drop 61, 919/541-2489.

16. ABSTRACT The report gives results of an evaluation of the economics of an oil-agglomeration process (with and without an oil recovery system) for recovering coal fines from a fine refuse stream of 105 ton/hr from a coal preparation plant. The two base case processes studied are oil-agglomeration processes: in one, heptane is used and recovered; and in the other, fuel oil is used and blended with the product. The economics for both processes were estimated with and without a pond credit (savings in coal preparation plant investment resulting from the smaller waste disposal pond needed for the oil-agglomeration process). The total capital investments for the recovery and non-recovery processes without a pond credit are $21 million and $13 million, respectively. Using pond credit, the capital investment for the recovery process is $9 million and a capital investment credit of $0.2 million is received for the nonrecovery process. The first-year annual revenue requirements for the recovery and nonrecovery processes are $6.4 million (0.86 $/million Btu) and $8.0 million (1.10 $/million Btu) with a pond credit and $8.5 million (1.15 $/million Btu) and $10.3 million (1.42 $/million Btu) without a pond credit, respectively. These costs compare quite favorably with an eastern bituminous coal which has a heating value of 11,000 Btu/lb and cost of 1.85 $/million Btu (40.70 $/ton).

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Fuel Oil	Pollution Control	13B	11H
Coal Preparation	Waste Disposal	Stationary Sources	08I	
Agglomeration	Economic Analysis		14G	
Coal Dust			21D	05C
Fines				
Heptanes			07C	

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 71
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

This report was prepared by the Tennessee Valley Authority and has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Tennessee Valley Authority or the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The economics of an oil-agglomeration process with and without an oil recovery system are evaluated for recovering coal fines from a fine refuse stream of 105 ton/hr from a coal preparation plant. The two base case processes studied are an oil-agglomeration process in which heptane is used and recovered and an oil-agglomeration process in which fuel oil is used and blended with the product. The economics for both processes are estimated with and without a pond credit (savings in coal preparation plant investment resulting from the smaller waste disposal pond needed for the oil-agglomeration process). The total capital investments for the recovery and nonrecovery processes without a pond credit are $21 million and $13 million, respectively. With the use of the pond credit, the total capital investment for the recovery process is $9 million and a capital investment credit of $0.2 million is received for the nonrecovery process. The first-year annual revenue requirements for the recovery and nonrecovery processes are $6.4 million (0.86 $/MBtu) and $8.0 million (1.10 $/MBtu) with a pond credit and $8.5 million (1.15 $/MBtu) and $10.3 million (1.42 $/MBtu) without a pond credit, respectively. These costs compare quite favorably with an eastern bituminous coal which has a heating value of 11,000 Btu/lb and cost of 1.85 $/MBtu (40.70 $/ton). Both the recovery and the nonrecovery processes appear to be economically feasible but the recovery process is the more cost-effective method for recovering fine coal from refuse streams.

CONTENTS

Abstract iii
Figures vi
Tables vii
Abbreviations and Conversion Factors viii

Executive Summary S-1

Introduction 1

Background 3

Premises 5
  Design Premises 5
    Feedstock 5
    Oil-Agglomeration Plant 5
    Oil Recovery System 6
    Ponds 6
    Raw Materials 7
  Economic Premises 7
    Capital Investment 7
    Annual Revenue Requirements 7

Process Descriptions 11
  Oil Agglomeration with Heptane Recovery 11
    Material Handling and Storage 13
    Oil-Agglomeration System 13
    Heptane Recovery System 23
  Oil Agglomeration without Oil Recovery 23
    Material Handling and Storage 24
    Oil-Agglomeration System 24

Results 31
  Capital Investment 31
  Annual Revenue Requirements 36
  Case Variations 40
  Effect of Oil Consumption on Annual Revenue Requirements 42

Conclusions 47

References 49

Preceding page blank

FIGURES

Number		Page
S-1	Oil-agglomeration process with heptane recovery	S-5
S-2	Oil-agglomeration nonrecovery process with fuel oil	S-7
S-3	First-year annual revenue requirements (with pond credit) for the recovery and nonrecovery processes	S-12
S-4	First-year annual revenue requirements (without pond credit) for the recovery and nonrecovery processes	S-13
1	Oil-agglomeration process with heptane recovery	14
2	Oil-agglomeration nonrecovery process with fuel oil	25
3	First-year annual revenue requirements (with pond credit) for the recovery and nonrecovery processes	44
4	First-year annual revenue requirements (without pond credit) for the recovery and nonrecovery processes	45

TABLES

Number		Page
S-1	Process Design Conditions	S-3
S-2	Summary of Capital Investments	S-8
S-3	Case Variation Cost Sensitivities	S-10
1	Capital Investment Cost Factors	8
2	Projected 1984 Unit Costs for Raw Materials, Labor, and Utilities	9
3	Levelized Annual Capital Charges for Regulated Utility Financing	9
4	Major Process Operating Conditions	12
5	Pond Data	13
6	Oil-Agglomeration Process with Heptane Recovery Material Balance	15
7	Equipment List, Oil-Agglomeration Process with Heptane Recovery	17
8	Oil-Agglomeration Nonrecovery Process with Fuel Oil Material Balance	26
9	Equipment List, Oil-Agglomeration Nonrecovery Process with Fuel Oil	27
10	Recovery Process Pond Costs and Data	32
11	Oil-Agglomeration Process with Heptane Recovery Capital Investment	33
12	Oil-Agglomeration Nonrecovery Process with Fuel Oil Capital Investment	34
13	Summary of Capital Investments	35
14	Oil-Agglomeration Process with Heptane Recovery Annual Revenue Requirements	37
15	Oil-Agglomeration Nonrecovery Process with Fuel Oil Annual Revenue Requirements	38
16	Summary of Annual Revenue Requirements	39
17	Case Variation Cost Sensitivities	41
18	Effect of Oil Consumption on Nonrecovery Process Costs	43

ABBREVIATIONS AND CONVERSION FACTORS

ABBREVIATIONS

aft^3/min	actual cubic feet per minute	kWh	kilowatthour
Btu	British thermal unit	lb	pound
^oF	degrees Fahrenheit	M	million
dia	diameter	min	minute
ft	feet	mm	millimeter
ft^2	square feet	MW	megawatt
ft^3	cubic feet	psia	pounds per square inch (absolute)
gal	gallon	sec	second
gpm	gallons per minute	sft^3/min	standard cubic feet per minute (60^oF)
hp	horsepower	wt	weight
hr	hour	yd^3	cubic yard
in.	inch	yr	year
k	thousand		
kW	kilowatt		

CONVERSION FACTORS

EPA policy is to express all measurements in Agency documents in metric units. Values in this report are given in British units for the convenience of engineers and other scientists accustomed to using the British systems. The following conversion factors may be used to provide metric equivalents.

To convert British		Multiply by	To obtain Metric	
ac	acre	0.405	hectare	ha
Btu	British thermal unit	0.252	kilocalories	kcal
^{o}F	degrees Fahrenheit minus 32	0.5556	degrees Celsius	^{o}C
ft	feet	30.48	centimeters	cm
ft^2	square feet	0.0929	square meters	m^2
ft^3	cubic feet	0.02832	cubic meters	m^3
ft/min	feet per minute	0.508	centimeters per second	cm/s
ft^3/min	cubic feet per minute	0.000472	cubic meters per second	m^3/s
gal	gallons (U.S.)	3.785	liters	L
gpm	gallons per minute	0.06308	liters per second	L/s
hp	horsepower	0.746	kilowatts	kW
in.	inches	2.54	centimeters	cm
lb	pounds	0.4536	kilograms	kg
lb/ft^3	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3
lb/hr	pounds per hour	0.126	grams per second	g/s
psi	pounds per square inch	6895	pascals (newton per square meter)	Pa (N/m^2)
sft^3/min	standard cubic feet per minute ($60^{o}F$)	1.6077	normal cubic meters per hour ($0^{o}C$)	m^3/hr ($0^{o}C$)
ton	tons (short)	0.9072	metric tons	tonne
ton/hr	tons per hour	0.252	kilograms per second	kg/s
yd3	cubic yard	0.765	cubic meters	m^3

ECONOMIC EVALUATION OF OIL AGGLOMERATION FOR RECOVERY OF FINE COAL REFUSE

EXECUTIVE SUMMARY

INTRODUCTION

In this report, the economics of an oil-agglomeration process with and without an oil recovery system are evaluated. The two base case processes studied are an oil-agglomeration process using heptane with a heptane recovery system and an oil-agglomeration process using fuel oil that does not have an oil recovery system. The design data for the processes are based on information from vendors and researchers of oil-agglomeration and oil recovery systems. The economics of both processes are presented and compared, and several case variations are also examined.

BACKGROUND

Much of the coal lost in the waste from coal-cleaning plants consists of fine coal that is difficult to separate from noncoal minerals with conventional coal-cleaning techniques. The use of highly efficient coal-cleaning processes and cleaning of coal with finely dispersed pyrite, both of which necessitate more extensive use of fine coal-cleaning techniques, can dramatically increase the quantity of coal lost in the fine waste stream and the volume of fine waste produced. The coal loss represents a substantial potential resource and the waste itself, which consists of a slurry that is difficult to dewater and must be confined in a pond, poses increasingly serious economic and environmental problems. Consequently, interest in methods of cleaning and recovering fine coal has increased. One of the most effective methods is the oil-agglomeration process developed by the National Research Council of Canada.

The oil-agglomeration process is a means both of cleaning fine coal and of recovering the coal in a more useful form. Fine coal (in the minus 28-mesh range) is dispersed in an agitated vessel with a light oil such as heptane, fuel oil, or kerosene, and in some cases a small quantity of a binder such as asphalt is used. By carefully controlling the degree of agitation, the oil is dispersed in small droplets in which the coal and other oleophilic (oil attracted) minerals collect, forming small spherical particles. Over 90% of the coal in a fine coal slurry can be recovered in this manner. In spite of its effectiveness, the process has not gained

commercial acceptance because of the cost of the oil used. The agglomeration process becomes more economically attractive when designed for low oil-to-coal ratios; however, there is also a corresponding decrease in coal recovery efficiency and product quality. Recovery and reuse of the oil would allow the agglomeration process to operate at higher oil consumption levels with greater coal recovery and improved product quality.

The recovery process is ostensibly simple: the mechanically dewatered agglomerate is heated to vaporize the oil and the vapor is condensed to recover the oil. Several companies have investigated aspects of an oil-agglomeration process with an oil recovery system but many technical and practical details remain to be defined. The primary technical challenge is the development of a heating system that provides efficient and controllable heat transfer without thermal and mechanical damage to the particles.

DESIGN AND ECONOMIC PREMISES

The design and economic premises used in this study were developed by the Tennessee Valley Authority (TVA) for economic comparisons of processes related to coal-cleaning and emission control in electric utility applications. The conceptual process designs are based on information provided by vendors of oil-agglomeration and oil recovery equipment and systems. The plant is assumed to operate at 5,500 hr/yr for 30 years, with a total operating life of 165,000 hours.

The quantity and composition of the feed to the oil-agglomeration plant for this study are assumed to be similar to the fine coal refuse produced by the Breckenridge Camp No. 11 coal-cleaning plant near Breckenridge, Kentucky. The refuse consists of a 10% solids slurry produced at a rate of 5.8 million ton/yr. The solids have a maximum size of 28 mesh and consist of 47.5% coal, 2.5% pyrite, and 50% other noncoal minerals. The base case design conditions for the oil-agglomeration process (using heptane) with a heptane recovery system (recovery process) and the agglomeration process (using No. 2 fuel oil) without a recovery system (nonrecovery process) are shown in Table S-1. Heptane was selected as the oil in the recovery process because of its distinct properties which make it easier to recover than other oils, and No. 2 fuel oil was used in the nonrecovery process mainly because of its lower cost.

A 30-day-capacity holding pond and a 30-year-capacity waste disposal pond are provided for the oil-agglomeration plant as a replacement for the large volume waste disposal pond that would have been required for the coal-cleaning plant if the waste had not been processed. The waste disposal ponds are square earthen-diked impoundments with a median diverter dike and a 12-inch clay lining.

Raw materials consist of a propane precipitated asphalt at 189.2 $/ton and commercial grades of heptane, No. 2 fuel oil, and kerosene at 1.60, 1.09, and 1.32 $/gal, respectively. All raw materials are delivered

TABLE S-1. PROCESS DESIGN CONDITIONS

	Process	
	Heptane with recovery	Fuel oil without recovery
Feedstock		
Rate, Mlb/hr	2.1	2.1
Slurry concentration, % solids	10	10
Solids composition, % by wt (dry)		
Coal	47.5	47.5
Noncoal minerals	50	50
Pyrite	2.5	2.5
Operating Conditions		
Time, hr/yr	5,500	5,500
Coal recovery, % of coal feed	92	90
Oil, % of undried product	18[a]	6.1[b]
Asphalt, % of undried product	2	0
Oil recovery, % of oil feed	97.7	0
Product[c]		
Production, ton/yr	289,000	302,000
Solids composition, % by wt (dry)		
Coal	89	83
Noncoal minerals	8	14
Sulfur	3	3
Water	<5	30
Heating value, Btu/lb (dry)	12,900	12,000
Waste		
Rate, Mlb/hr	1.9	1.9
Solids, %	5	5
Coal, % of waste	0.3	0.4

a. This number corresponds to 14.1% oil based on the weight of the feed solids and 21.4% oil based on the dry weight of the agglomerated product (water-free basis).

b. This number corresponds to 5.0% oil based on the weight of the feed solids and 8.7% oil based on the dry weight of the agglomerated product (water-free basis).

c. All product percentages and the heating values are based on the dry weight of the product (coal and all noncoal minerals, including pyrite) and do not include the weights or effects on heating value of residual oil, asphalt, or water (the heating values of the residual oil and asphalt are taken into account in the economics).

by rail in tank cars and are stored in tanks sized to provide a storage capacity of 30 days.

The economic estimates consist of capital investments and both first-year and levelized annual revenue requirements. Capital investments are based on mid-1982 costs and annual revenue requirements are projected to 1984 and are based on 5,500 hr/yr of operation at full capacity. The capital investments also include pond credits which are determined by subtracting the cost of the 30-day-capacity holding pond and the 30-year-capacity waste disposal pond for the agglomeration plant from the cost of the coal-cleaning plant 30-year-capacity waste disposal pond.

PROCESS DESCRIPTION

Oil Agglomeration with Heptane Recovery

The process consists of four identical trains of agglomeration and heptane recovery equipment, supplied by a single feed tank and raw material storage and supply system. The flow diagram is shown in Figure S-1. The agglomeration plant is designed to process a 10% solids slurry at a rate of 2.1 million lb/hr (about 4,000 gal/min of slurry) for 5,500 hr/yr for 30 years. The 10% solids slurry is recovered from the coal-cleaning plant holding pond and pumped to a scalping screen that removes particles over 0.5 mm in size. The slurry that passes through the screen is stored in an agitated tank from which it is pumped to the high-shear mix tank. Along with the slurry, 18% heptane and 2% asphalt (both based on agglomerated product from the screen) are added to the mix tank. The high degree of agitation produces very fine droplets of heptane and asphalt in which the coal and other oleophilic minerals agglomerate. The slurry flows to the low-shear mix tank which has a lesser degree of agitation and allows the small agglomerates formed in the high-shear mix tank to coalesce into particles 2 to 3 mm in diameter (an adequate size particle for thermal drying).

The slurry flows by gravity from the low-shear mix tank to a vibrating screen which removes the agglomerated particles. The unagglomerated particles (mostly noncoal minerals) and liquid drain to a refuse tank. The agglomerated particles are transferred by belt conveyor to the heptane recovery system. The agglomeration plant is designed to recover 92% of the coal in the waste and produce 289,000 ton/yr of product containing 89% coal, 8.0% mineral matter, and 3.0% sulfur with a heating value of 12,900 Btu/lb (not including residual heptane and the asphalt binder).

The recovery system consists of a fluidized-bed dryer; a particle purge vessel; and associated gas circulating, solids collecting, and condensing equipment. The particles are transported from the feed bin in a screw conveyor and fed to the dryer through an air lock. The particles are fluidized with a heated mixture of 60% heptane and 40% water vapors which vaporizes 95% of the heptane and water in the particles.

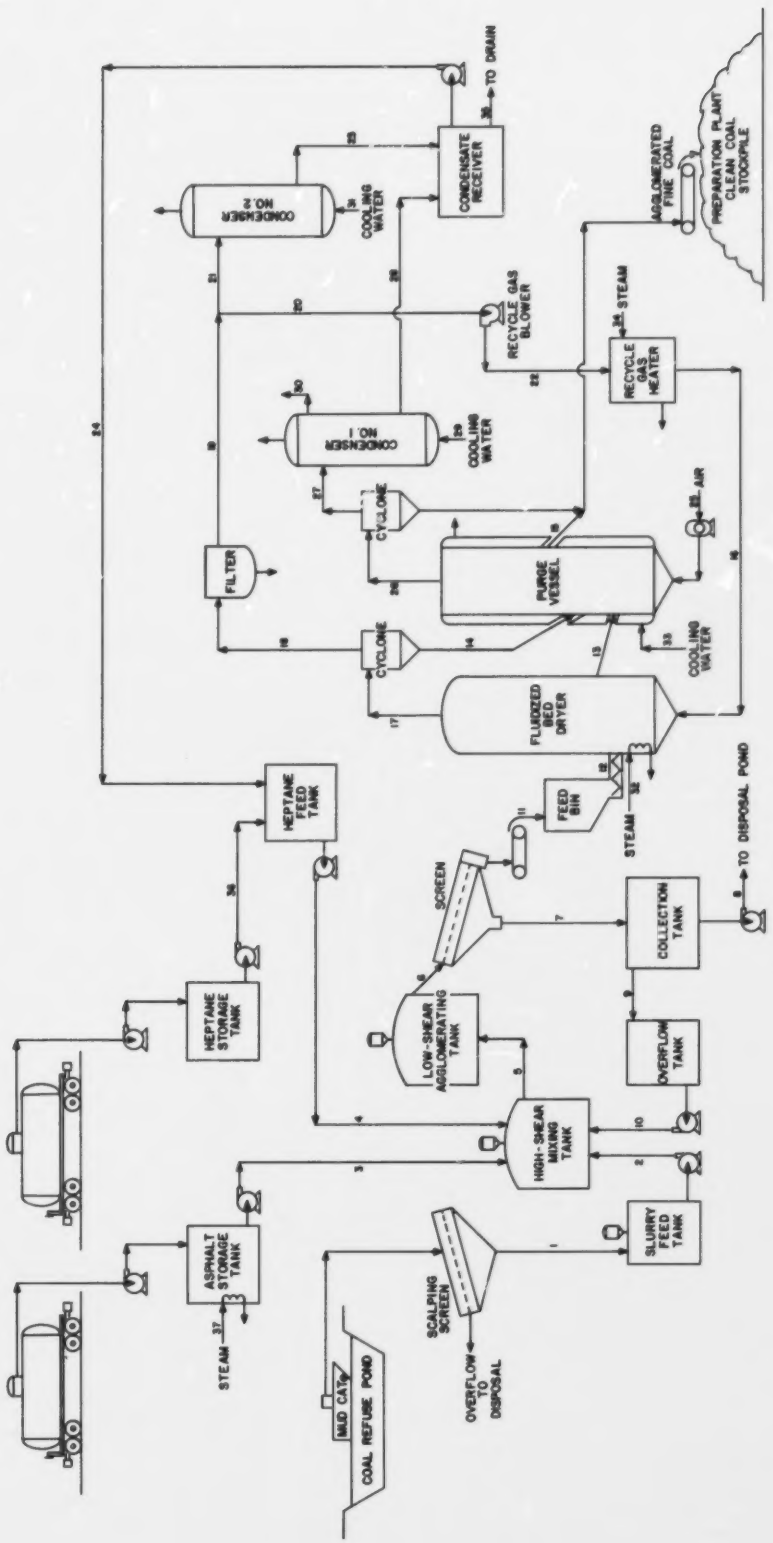

Figure S-1. Oil-agglomeration process with heptane recovery.

The gas from the dryer passes through a cyclone and filter to remove entrained solids. Two-thirds of the gas is recycled through a compressor and heated to 465°F before entering the dryer and one-third is passed through a water-cooled shell-and-tube heat exchanger that condenses and cools the heptane and water to 100°F. The condensate drains to a condensate tank in which the heptane and water separate. The heptane is returned to the agglomeration system and the water is pumped to the waste pond. Approximately 97.7% of the heptane is recovered.

Oil Agglomeration without Oil Recovery

The nonrecovery process uses No. 2 fuel oil and is based on conditions typical of those conventional oil-agglomeration processes in which the quantity of oil used is minimized to reduce cost. The nonrecovery process differs from the recovery process by the use of a less expensive oil and a much lower oil content in the agglomerated product (6.1% fuel oil based on the agglomerated product from the screen--see Table S-1) and the absence of the oil recovery system. As a result of the lower oil content, the coal recovery is somewhat lower (90%) and the product particle size is smaller (+100 mesh). [The quantity of oil used in the agglomeration process has the greatest effect on the product particle size and coal recovery rate. The physical properties of the oil (i.e., density, viscosity, etc.) will have a slight effect, but were not evaluated in this study since their effect was considered to be very minor when compared to the effect of the oil level.] The flow diagram for the nonrecovery process is shown in Figure S-2. The equipment and process descriptions for the nonrecovery process are similar to the agglomeration circuit in the recovery process except for the deletion of the asphalt binder for the agglomerated coal which is not needed since the nonrecovery product is not thermally dried.

RESULTS

Capital investments and first-year and levelized annual revenue requirements are developed for the base case processes described in the preceding section. Several case variations and sensitivities are examined for the base cases, and the alternative of using kerosene or heptane instead of fuel oil is evaluated for the nonrecovery process.

Capital Investment

The summary of the capital investment estimates for the base case processes is shown in Table S-2. The total capital investment for the recovery process is $9 million with the pond credit and $21 million without the pond credit. The total capital investment for the nonrecovery process using fuel oil is almost $13 million without the pond credit and a capital investment credit of $0.2 million is received with the pond credit. The major capital investment difference for the base case processes is in the total process capital. The total process capital for the nonrecovery process is approximately 43% less than the recovery process. The smaller process capital cost for the nonrecovery process is due to the exclusion of

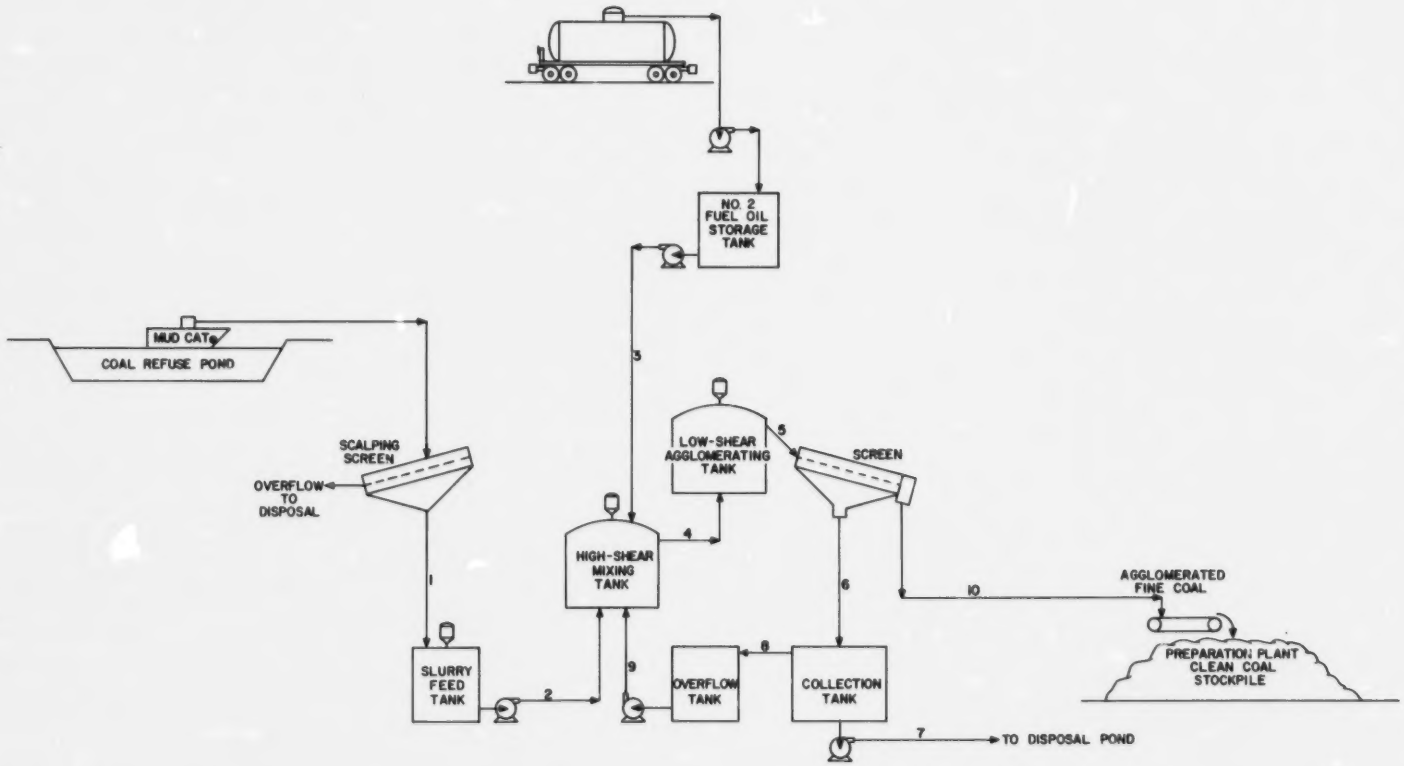

Figure S-2. Oil-agglomeration nonrecovery process with fuel oil.

the heptane recovery system, which accounts for approximately 43% of the total process capital for the recovery process.

TABLE S-2. SUMMARY OF CAPITAL INVESTMENTS

Investment area	Total cost, k$	
	Recovery process	Nonrecovery process with No. 2 fuel oil
Total process capital	10,015	5,668
Total indirect investment	6,546	3,704
Working capital	909	1,109
Other capital charges	4,029	2,279
Total capital investment excluding pond credit	21,499	12,760
Pond credit	(12,168)	(12,926)
Total capital investment	9,331	(166)

The pond credit for the nonrecovery process is approximately 6% higher than the recovery process. This is a result of the nonrecovery process using a lower oil-to-coal ratio, and thus having lower coal but higher ash recoveries, which subsequently decrease the quantity of waste solids and require a smaller refuse pond for the nonrecovery process.

The pond credit has a very large effect on the capital investments and the difference is illustrative of the large cost associated with pond disposal of large volumes of waste. The pond credit reduces the total capital investments for the recovery process by approximately 57% and the nonrecovery process by more than 100%.

Annual Revenue Requirements

The first-year annual revenue requirements for the recovery process are $6.4 million, as compared with $8.0 million for the nonrecovery process with fuel oil, including the pond credit in both cases. The difference in annual revenue requirements between the two processes is due mainly to the larger quantity of oil consumed by the nonrecovery process, which replaces that lost in the coal agglomerates. Even though a heat credit is applied for the oil, it is not enough to offset the difference between the cost of the two processes. The first-year unit revenue requirements are 0.86 $/MBtu (22 $/ton) for the recovery process and 1.10 $/MBtu (27 $/ton) for

the nonrecovery process, including the pond credit in both cases. Without the pond credit, the unit costs are 1.15 $/MBtu (30 $/ton) for the recovery process and 1.42 $/MBtu (34 $/ton) for the nonrecovery process. These costs compare quite favorably with an eastern bituminous coal which has a heating value of 11,000 Btu/lb and cost of 1.85 $/MBtu (40.70 $/ton).

Case Variations

Since the design data for the processes are based on laboratory tests, several case variations and sensitivities are examined, as shown in Table S-3, for different pond credits, raw material costs, asphalt contents, and coal recoveries for the recovery process and the nonrecovery process with fuel oil. Different heptane recoveries and purge gases are also evaluated for the recovery process, along with the effects of including a pelletizing system for the product. The effects of using alternate agglomerating agents (oils) and of using a centrifuge to separate the liquid from the coal agglomerates are also evaluated for the nonrecovery process.

The pond credit has a major effect on both the capital investment and annual revenue requirements of both processes. With the pond credit, the capital investments for the recovery and nonrecovery processes are 57% and over 100% lower, respectively, than capital investments without pond credits. The first-year annual revenue requirements for the recovery and nonrecovery processes are increased 34% and 28% without the pond credit. The smaller percentage increase for the nonrecovery process results from the greater importance of the raw material cost, which is the predominant factor in its annual revenue requirements. The recovery and nonrecovery processes are also sensitive to raw material price, asphalt content, and coal recovery rates. The recovery process is also sensitive to heptane recovery rates and slightly sensitive to the type of purge gas selected. The addition of a pelletizing area to the recovery process increases the capital investments and annual revenue requirements by 13% and 23%, respectively, and the use of a centrifuge in the nonrecovery process increases its capital investment and annual revenue requirements by 150% and 10%, respectively. However, the cost for adding the pelletizing area to the recovery process (first-year annual revenue requirements of 1.06 $/MBtu with the pond credit) and using a centrifuge in the nonrecovery process (first-year annual revenue requirements of 1.21 $/MBtu with the pond credit) is still less than the cost of the premise coal at 1.85 $/MBtu.

The first-year annual revenue requirements of the nonrecovery process are projected for two other agglomerating agents (heptane and kerosene). The other nonrecovery processes in which the weight of heptane and kerosene in the product is the same as for the fuel oil process have substantially higher annual revenue requirements--$10.5 million for the kerosene process and $15.3 million for the heptane process, as compared with $8.0 million for the fuel oil process. The predominant difference is the oil costs--1.09, 1.32, and 1.60 $/gal for fuel oil, kerosene, and heptane, respectively.

TABLE S-3. CASE VARIATION COST SENSITIVITIES

Variation	Oil agglomeration with heptane recovery				Oil agglomeration with fuel oil			
	Capital investment[a]		Annual revenue requirements[b]		Capital investment[a]		Annual revenue requirements[b]	
	M$	Change, %	$/MBtu	Change, %	M$	Change, %	$/MBtu	Change, %
Pond credit								
Base case	9.3		0.86		(0.2)		1.10	
50% of base case	15.4	+66	1.00	+16	6.3	+3,250	1.26	+15
No pond credit	21.5	+131	1.15	+34	12.8	+6,500	1.42	+29
Raw materials price[c]								
80% of base case	9.29	-0.1	0.79	-8	(0.3)	-50	0.86	-22
Base case	9.3		0.86		(0.2)		1.10	
140% of base case	9.4	+1	1.01	+17	0.1	+150	1.60	+45
Asphalt used[d]								
50% of base case	9.1	-2	0.78	-9				
Base case	9.3		0.86		(0.2)		1.10	
150% of base case	9.6	+3	0.94	+9	1.0	+600	1.41	+28
Coal recovery[e]								
90% of base case	9.5	+2	0.95	+10	1.5	+850	1.27	+15
Base case	9.3		0.86		(0.2)		1.10	
105% of base case	9.1	-2	0.82	-5	(1.2)	-500	1.02	-7
Heptane recovery								
80%	10.0	+8	1.96	+128				
90%	9.6	+3	1.34	+56				
95%	9.4	+1	1.03	+20				
Base case (97.7%)	9.3		0.86					
99.7%	9.2	-1	0.74	-14				
Purge gas								
Base case (air)	9.3		0.86					
Inert gas	9.2	-1	0.74	-14				
Nitrogen	9.8	+5	0.75	-13				
Pelletization								
Base case	9.3		0.86					
Base case with pelletization	10.5	+13	1.06	+23				
Centrifuge								
Base case					(0.2)		1.10	
Base case with centrifuge					0.1	+150	1.21	+10
Oils								
Base case (fuel oil)					(0.2)		1.10	
Kerosene					0.1	+150	1.45	+32
Heptane					0.5	+350	2.11	+92

a. 1982 dollars.
b. First-year annual revenue requirements in 1984 dollars.
c. Asphalt and heptane or fuel oil.
d. 1%, 2%, and 3% of undried product for the recovery process; 0% and 3% for the nonrecovery process.
e. 83%, 92%, and 97% for the recovery process; 81%, 90%, and 95% for the nonrecovery process.

Effect of Oil Consumption on Annual Revenue Requirements

The effect of the quantity of oil used on the cost of the nonrecovery processes is shown in Figures S-3 and S-4 in comparison with the recovery process at different oil recovery efficiencies. The recovery process has the same oil and asphalt content in the agglomerated product as the base case processes--18% oil and 2% asphalt in the agglomerated coal.

The nonrecovery process annual revenue requirements increase rapidly with increasing oil consumptions. This is primarily due to the higher consumption of fuel oil which is the predominant cost factor in the first-year annual revenue requirements. The cost of the nonrecovery product with the pond credit exceeds the cost of the premise coal (1.85 $/MBtu) at oil levels of 11% or higher (9% without the pond credit as shown in Figure S-4).

The recovery process annual revenue requirements are not related to oil content in the agglomerated coal but to the efficiency of the oil recovery system. As the recovery efficiency decreases (percent oil loss increases), the annual revenue requirements increase rapidly as shown in Figures S-3 and S-4. At an 18% to 20% oil loss in the recovery process, the cost of the product with the pond credit exceeds that of the premise coal at 1.85 $/MBtu. With no pond credit, the cost of the recovery product exceeds the premise coal at an oil loss of approximately 13.5%.

At the base case conditions evaluated in this study, the recovery process is less expensive to operate than the nonrecovery process. Also, a poorer quality of product is produced in the nonrecovery process, and there may be greater uncertainty concerning the capability of the nonrecovery process (at the low oil levels) to actually yield a product suitable for use in a pulverized-coal-fired boiler. However, the nonrecovery process could be economically competitive if lower than base case oil recoveries are achieved in the recovery process. As shown in Figure S-3, the first-year annual revenue requirement with pond credits for the recovery process with only 2.3% oil loss (base case) is equivalent to the revenue requirements for the nonrecovery process at an oil level of 4.5% in the product, but at oil losses greater than 6.5% (recoveries less than 93.5%), the first-year annual revenue requirements for the base case nonrecovery process (oil level of 6.1% in the product) with pond credits are less than the recovery process.

CONCLUSIONS

Based on typical costs for coal, the oil-agglomeration process appears to be an effective method for recovering coal fines from coal-cleaning plant refuse. Both the recovery and the nonrecovery processes appear to be economically feasible methods but, depending on the base case amounts of oil used in the two processes and the efficiency of the oil recovery in the recovery system, the recovery process is the more cost-effective method. As a result of the more favorable economics for the recovery process at the

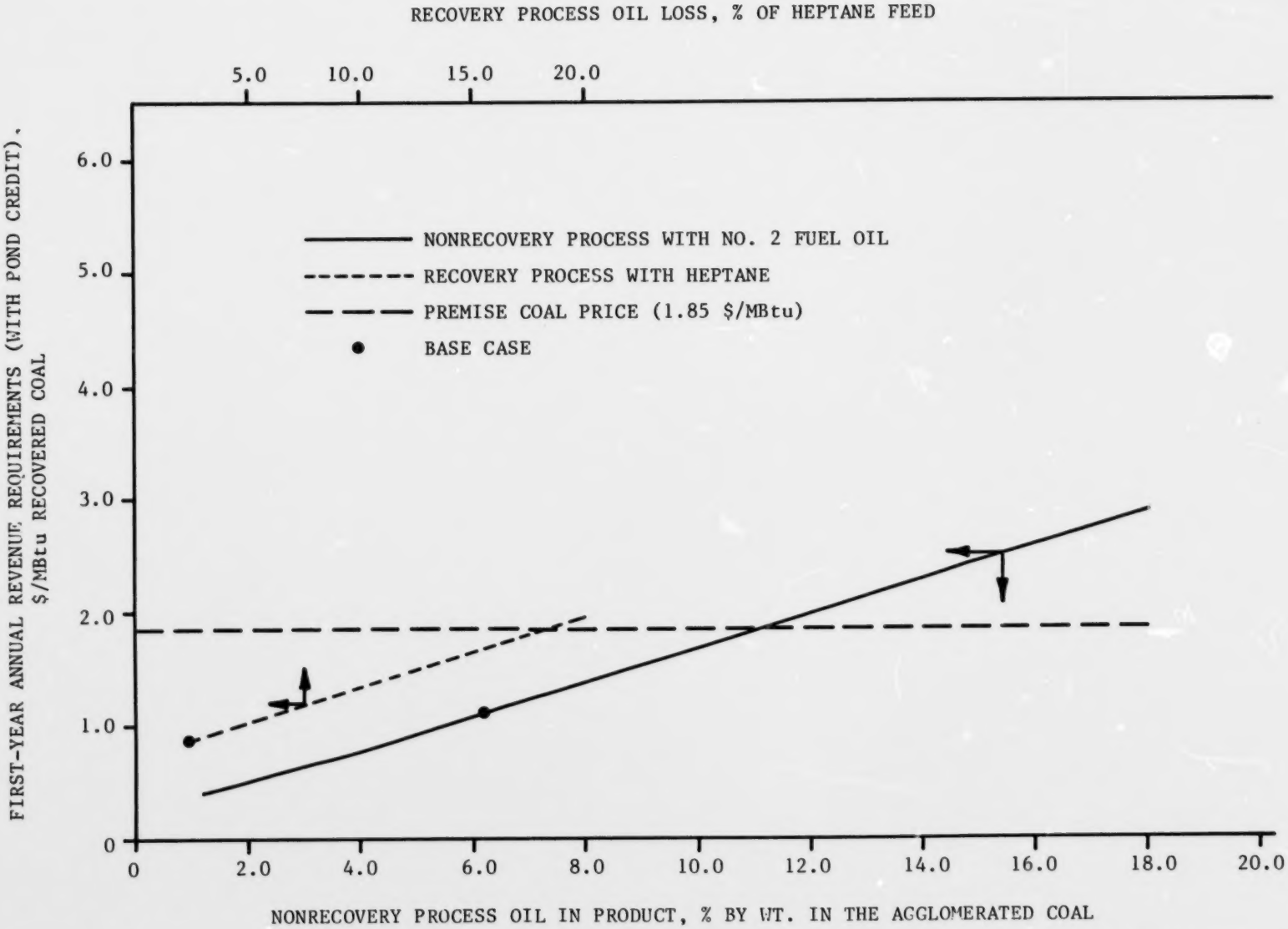

Figure S-3. First-year annual revenue requirements (with pond credit) for the recovery and nonrecovery processes.

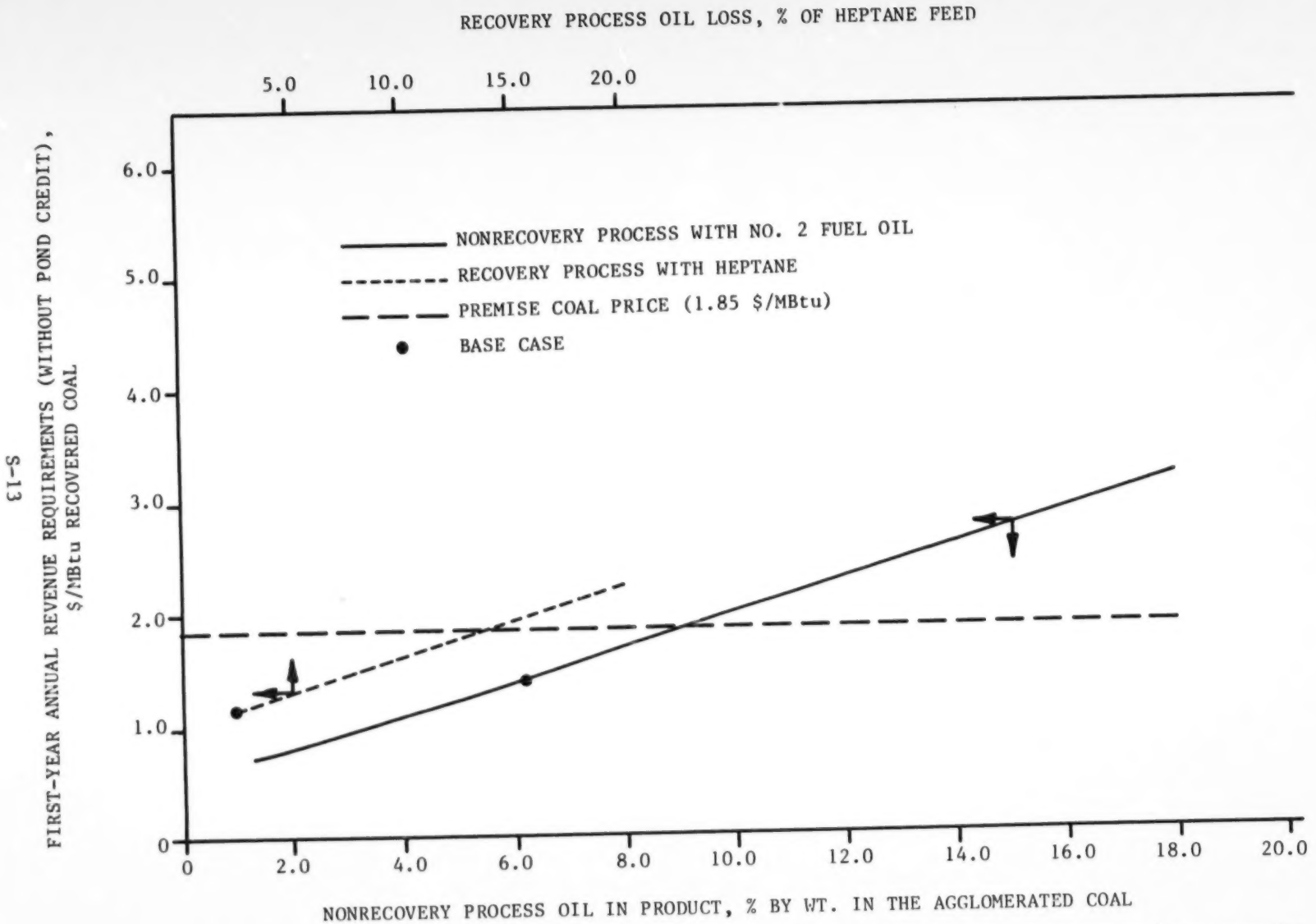

Figure S-4. First-year annual revenue requirements (without pond credit) for the recovery and nonrecovery processes.

higher oil recovery efficiencies (greater than 93%), it is recommended that this technology be tested to determine if the recovery system can be operated with the desired efficiency. If the recovery system cannot operate at the higher oil recovery efficiencies (greater than 93%), examination of the nonrecovery process may be advisable.

ECONOMIC EVALUATION OF OIL AGGLOMERATION FOR RECOVERY OF FINE COAL REFUSE

INTRODUCTION

In this study, the economics of an oil-agglomeration process for recovery of fine coal refuse are evaluated.

Oil agglomeration is a method of concentrating fine oleophilic (oil attracted) particles by dispersing a light oil as fine droplets in a water slurry of the particles. The oleophilic particles collect in the oil while the hydrophilic particles remain dispersed in the water phase. The oil-agglomeration process--also called the spherical-agglomeration process--was developed by the National Research Council of Canada about 10 years ago (1). The Arcanum Corporation, a subsidiary of Industrial Tectonics, Inc., obtained a license for the technology and developed a process to produce small tungsten carbide spheres with densities equivalent to those produced with normal powder compacting and pelletizing methods. As a result of this work, Arcanum investigated other applications for the process and has gained wide experience in agglomeration techniques for the beneficiation of minerals and coal, dewatering of slurries, and the agglomeration of fine coals to improve their handling characteristics.

The Chemistry Division of the National Research Council of Canada has also made various studies of oil-agglomeration technology. They supervised the installation of two pilot plants in eastern Canada capable of producing 1 to 2 ton/hr of agglomerated coal fines. The coal-agglomeration technology has also been successfully applied by Broken Hill Products in Australia. They operate a pilot plant to remove noncoal mineral matter from coal and a full-scale plant for the recovery of fine coal at the Point Kebler Steel Works (2).

In this study, the economics of the oil-agglomeration process with and without oil recovery are compared for a system in which a fines refuse stream of 105 ton/hr from a coal preparation plant is treated. (A coal preparation plant capacity of 900 ton/hr of coal, with no fine coal-cleaning circuit, would be a typical size plant producing this quantity of fines.) The two base case processes studied are an oil-agglomeration process in which heptane is used and recovered (recovery process) and an oil-agglomeration process in which fuel oil is used and blended with the product (nonrecovery process). The recovery process is based on operation at a much higher oil-to-solids ratio than the nonrecovery process to yield

a higher coal recovery (92% for the recovery process as compared to 90% for the nonrecovery process) and larger product particle size (2 to 3 mm as compared to 0.15 mm) which is necessary with the thermal drying step used in the recovery process. (The higher quantity of oil can be used without significant economic effects since this is a recovery process.) The intermediate agglomerate material also has a moisture content of 16% in the recovery process as compared to 30% in the nonrecovery process because of the higher oil level used in the recovery process which produces a better quality product with a lower moisture content.

The economics of both processes are presented and compared, and several case variations are also examined.

BACKGROUND

There are few methods of separating fine coal particles from noncoal minerals and water. (Fine coal is generally regarded as having a particle size less than 28 mesh--about 0.5 mm.) All of these methods are based on the difference in surface properties between coal and the various noncoal minerals in coal that permit the concentration of coal in one phase of a 2-phase gas-liquid or liquid-liquid system. Froth flotation, in which fine bubbles of air are dispersed in a chemically conditioned slurry of coal and water, is the only method in commercial use. Because of its hydrophobic surface properties, the coal becomes concentrated in the air bubbles and is carried to the surface, forming a froth that can be removed. The method has inherent limitations that can only be reduced in degree by improvements in the equipment and chemical conditioning. Often only about one-half of the coal is recovered and the product is a paste with a high water content.

In spite of the shortcomings of froth flotation, it is being used with increasing frequency because of the need for high levels of cleaning and the growing use of poorer quality coals. In most cases, highly efficient cleaning requires reduction of the coal to a small particle size. This is particularly true of poorer quality coals that are more likely to contain highly dispersed noncoal mineral matter that requires a high degree of comminution to release it from the coal matrix. As a result, coal-cleaning plants are producing ever increasing quantities of wastes in the form of slurries with a high coal content. Not only does the waste represent a substantial potential resource, disposal of the huge quantities of slurry presents serious economic and environmental problems since most refuse is disposed in landfills or disposal ponds. These developments have spurred interest in fine coal processing technology, both to develop better fine coal-cleaning processes and to recover the coal in coal-cleaning plant wastes.

Oil agglomeration is the most efficient and highly developed alternative to froth flotation. It is based on the same principles as froth flotation but uses a liquid-liquid system. A light oil, called a bridging oil (and in some cases a binder such as asphalt), is dispersed as fine droplets in a water slurry of fine coal. The strong oleophilic properties of the coal cause it to concentrate in the oil droplets while many of the hydrophilic noncoal minerals remain dispersed in the water phase. The attractive forces between the coal and oil are sufficient to form cohesive particles larger than 3 mm in diameter, which with the help of the binder, remain as coherent pellets when screened from the liquid.

In its present form, oil agglomeration provides very little reduction in sulfur content because pyrite is an oleophilic mineral with surface properties similar to coal. This is also true of froth flotation separation methods. There are, however, methods of attaining separation of coal and pyrite by either froth flotation or oil agglomeration. The U.S. Bureau of Mines has developed a 2-stage froth flotation method for reducing the sulfur content of fine coal (3) and some investigations have been made using iron-oxidizing bacteria of the Ferrobacillus thiobacillus group to form a coating of soluble iron compounds on the pyrite, which renders it hydrophilic (1).

The oil-agglomeration process has several advantages over other fine coal-cleaning and recovery processes. It is capable of agglomerating very fine coal particles in the 200-mesh size range (about 0.1 mm) at recovery rates over 90%. The high level of attraction between the coal and oil also excludes much of the water from the particle so that most of the moisture in the product is easily removable surface moisture. For agglomerates over 2 mm in size, moisture contents of less than 10% can be obtained and the agglomerates dry to 3% to 5% moisture simply by overnight storage (1). In addition, the product is in the form of pellets rather than small loose particles that are difficult to handle.

Such high efficiencies, however, require large quantities of oil and binder--up to one-fourth by weight of the slurry solids--which pose a heavy economic burden on use of the process to clean or recover coal. The cost of the oil and binder can easily exceed the value of the recovered coal even if a credit is given for the heating value of the oil and binder. To be economically feasible, the process must be operated at low oil-to-coal ratios; however, lowering these ratios usually results in decreases in efficiency and product quality. Consequently, in spite of its high technical potential, the process has attracted only limited interest as a method of coal cleaning and coal waste recovery.

Recovery and reuse of the oil is an obvious method of avoiding the economic limitations placed on the process and would allow the process to be used at oil levels that maximize the potential of the oil-agglomeration process. The recovery process is ostensibly simple: the particles are heated to vaporize the oil (which, if a binder is used, is not needed to hold the particles together) and the oil is then condensed. The primary technical challenge is the development of a heating system that provides efficient and controllable heat transfer without thermal and mechanical damage to the particles. Oil recovery processes, in conjunction with oil-agglomeration processes for coal, have been investigated on a pilot scale but they have not been demonstrated as functional large-scale systems.

PREMISES

The design and economic premises used in this study were developed by the Tennessee Valley Authority (TVA) for economic evaluations and comparisons of processes related to coal cleaning and emission control in electric utility applications. The conceptual process designs were developed from vendor information based on a specific coal-cleaning plant waste. General design and operating features are based on typical industry practices and electric utility operations. The economic evaluation, consisting of determinations of the capital investment, first-year annual revenue requirements, and levelized annual revenue requirements, is based on regulated utility economics.

DESIGN PREMISES

The process designs are based on information provided by the Arcanum Corporation (4), the Davy McKee Corporation (5), and several oil-agglomeration researchers (6). Some of the information was developed from laboratory tests of the coal-cleaning waste used as the basis for the designs.

Feedstock

The feedstock is assumed to be fine coal refuse produced by the Camp Breckenridge No. 11 coal-cleaning plant near Breckenridge, Kentucky, in which a western Kentucky bituminous coal is cleaned for use at TVA's Cumberland Steam Plant. The refuse consists of a 10% solids slurry produced at a rate of 5.8 million ton/yr which is equivalent to 105 ton/hr of dry coal fines. The solids have a maximum size of 28 mesh and consist of 47.5% coal, 2.5% pyrite, and 50% other noncoal minerals.

Oil-Agglomeration Plant

The oil-agglomeration plant is situated adjacent to the coal-cleaning plant. It is designed to process all of the waste slurry produced by the coal-cleaning plant in an operating period of 5,500 hr/yr (2.1 million lb/hr of slurry). A 30-day-capacity holding pond is provided for surge capacity. All facilities are designed for a 30-year life.

The process with oil recovery is designed to recover 92% of the coal in the feedstock and to produce 2- to 3-mm particles (an adequate size particle for thermal drying) containing 89% coal, 8% noncoal mineral matter other than pyrite, 3% sulfur (all on a dry basis excluding oil and

asphalt), and 16% water. The oil, commercial-grade heptane (which was selected because it is easier to recover than other oils), and the binder, asphalt, are used to produce an agglomerated product with 18% heptane and 2% asphalt.

The process without oil recovery is designed to recover 90% of the coal in the feedstock and to produce 0.15-mm particles containing 83% coal, 14% noncoal mineral other than pyrite, and 3% sulfur (all on a dry basis excluding oil). Fuel oil without any binder is used to produce an agglomerated product containing 30% water and 6.1% oil.

The basis for determining the design conditions for the oil-agglomeration plant is the size of coal agglomerates to be produced. The size (and quality) of the coal agglomerates is directly dependent upon the quantity of oil used in the process. Large quantities of oil produce large agglomerates with high coal and low moisture contents; whereas, small amounts of oil produce smaller agglomerates with lower coal and higher moisture contents. Also, when considering using an oil recovery system in conjunction with the oil-agglomeration process (in order to reduce the operating cost by recovering the oil), an adequate size particle must be produced and used in the dryer in order to prevent excessive particle attrition and coal loss.

Oil Recovery System

Multiple trains of fluidized-bed dryers are used in the recovery process. The heating-fluidizing medium is a superheated vapor of heptane and water that flows through the bed at a superficial velocity of 1 ft/sec. The dried particles are purged with air to cool them and remove the remaining heptane and water. Elutriated particles are collected with cyclones and fabric filters. The vapors are condensed in water-cooled heat exchangers. The system is designed to recover 97.7% of the heptane in the particles and dry the particles to a moisture content of a few percent.

Ponds

A 30-day-capacity feedstock holding pond and a 30-year-capacity waste disposal pond are provided for the oil-agglomeration plant as a replacement for a larger coal-cleaning plant waste disposal pond. The waste disposal ponds are square earthen-diked impoundments with a median diverter dike and a 12-inch clay lining. The ponds are assumed to be constructed on level land using materials excavated from the site. The depth-area relationship minimizes the sum of land costs and construction costs. The 30-day holding pond is based on the total volume of the 10% solids slurry from the coal-cleaning plant. The waste pond volume is based on 30-year waste production at a settled dry bulk density of 50 lb/ft^3.

A credit is assumed in the economic evaluation for a 30-year-capacity pond for unprocessed waste from the coal-cleaning plant. The volume is also based on a settled dry bulk density of 50 lb/ft^3.

Raw Materials

The heptane and asphalt are delivered by rail in tank cars and are stored in tanks sized to provide a storage capacity of 30 days. The asphalt is propane precipitated and has a softening point of 170°F to 180°F and a penetration grade of 0 to 10. The other raw materials are standard commercial grades.

ECONOMIC PREMISES

Capital Investment

Capital investments are based on a 3-year construction period, beginning early in 1981 and ending in late 1983, with mid-1982 costs representing the midpoint of the construction schedule.

The direct capital investment consists of all costs, excluding land, for equipment, materials, and labor to install the system. The installed cost includes labor; piping; foundations; excavations; structural steel; electrical; a 7% overtime premium for construction labor; and 6% of the total process capital for services, utilities, and miscellaneous. All equipment and direct construction costs associated with waste disposal and pond construction are included in waste disposal costs.

Indirect investment consists of costs for engineering design and supervision, architect and engineering contractor, construction expense, contractor fees, and contingency. They are calculated as a percentage of the direct, indirect, and fixed investments as shown in Table 1. The fixed investment is the sum of the direct and indirect investment. Interest during construction is based on a 10% weighted cost of capital, assuming 25% of the construction expenditures in the first year, 50% in the second year, and 25% in the third year of the construction schedule. Startup costs are assumed to occur late in the project schedule such that no charges are incurred for the use of money to pay startup costs.

The cost of land associated with the process and waste disposal area is charged at 5,000 $/acre. Working capital is the sum of 1 month of raw material costs, 1.5 months of conversion costs, 1.5 months of plant and administrative overhead costs, and 3% of the total direct capital investment.

Annual Revenue Requirements

Annual revenue requirements are projected to 1984 and are based on 5,500 hr/yr of operation at full capacity. Annual revenue requirements consist of the direct and indirect operating and maintenance costs and capital charges. Capital charges are levelized in both first-year and levelized annual revenue requirements. Operating and maintenance costs are also levelized in the levelized annual revenue requirements. The

levelizing factor consists of an annual 10% discount factor and an annual 6% inflation rate over the 30-year project life.

TABLE 1. CAPITAL INVESTMENT COST FACTORS

	% of direct investment	
	Process	Pond
Indirect Investment		
Engineering design and supervision	7	2
Architect and engineering contractor	2	1
Construction expense	16	8
Contractor fees	5	5
Total indirect investment	30	16
	% of direct and indirect investment	
Contingency	20	10
	% of total fixed investment	
Other Investment		
Allowance for startup and modifications	8	0
Interest during construction	15.6	15.6

Operating and Maintenance Costs--

Direct costs consist of raw materials and conversion costs, including labor and utilities. The projected 1984 unit costs for raw materials, labor, and utilities are shown in Table 2. Maintenance costs are estimated as a percentage of the direct investment and are varied according to process complexity and size. (A percentage factor of 6% is used for oil-agglomeration and heptane recovery systems and 3% for disposal ponds.) Utilities are determined directly from the process equipment requirements and raw materials from the material balance. Plant and administrative overhead is 60% of the conversion costs excluding utilities.

Capital Charges--

Capital charges represent the recovery of the capital investment over the 30-year life of the system. The components of the levelized annual capital charges, representing an annual charge of 14.7% of the total capital investment, are shown in Table 3.

TABLE 2. PROJECTED 1984 UNIT COSTS FOR RAW MATERIALS, LABOR, AND UTILITIES

	$/unit
Raw materials	
Heptane	1.60/gal
Asphalt	189.20/ton
Natural gas	4.29/MBtu
Nitrogen	0.48/100 ft3
No. 2 fuel oil	1.09/gal
Kerosene	1.32/gal
Labor	
Operating labor	15.00/man-hr
Analyses	21.00/man-hr
Utilities	
Fuel	1.60/gal
Process water	0.14/kgal
Electricity	0.037/kWh
Steam	2.50/klb

TABLE 3. LEVELIZED ANNUAL CAPITAL CHARGES FOR REGULATED UTILITY FINANCING

	% of total capital investment
Capital recovery factor	10.61
Interim replacements	0.56
Insurance and property taxes	2.50
Income tax	4.31
Investment credit	(1.92)
Accelerated depreciation	(1.36)
Total levelized annual capital charge	14.70

PROCESS DESCRIPTIONS

The base case process conceptual designs are prepared from process descriptions, material balances, flow diagrams, and equipment lists. These designs are based on vendor information and do not represent specific installations. The two base case processes are an oil-agglomeration process in which heptane is used and recovered (recovery process) and an oil-agglomeration process in which fuel oil is used and blended with the product (nonrecovery process). (Case variations differ from the descriptions of the base cases only in the particular variable changed.) The recovery process is based on operation at a much higher oil-to-solids ratio, and thus has a higher coal recovery rate and produces a better product (higher heating value, larger particle size, and lower moisture content) than the nonrecovery process.

The major operating conditions and product properties for both processes are shown in Table 4. The same coal feedstock and its supply method are used for both processes. The waste from the coal-cleaning plant is stored in a 30-day-capacity holding pond, from which it is recovered by two Mud Cats (a tradename for a small floating suction dredge) and pumped to a scalping screen, which removes solids greater than 0.5 mm in size, from which it flows by gravity to an agitated feed tank with an 8-hour capacity. The volumetric flow rate of 2.1 million lb/hr of the feed slurry is about 4,000 gal/min. The agglomeration plant designs are based on operating at this feed rate for 5,500 hr/yr for 30 years.

Costs for three ponds are considered in the economic evaluation: the holding pond for the coal-cleaning plant waste, the agglomeration plant waste disposal pond, and a hypothetical disposal pond which would have been needed by the coal-cleaning plant if its waste was not processed. The pond designs are discussed in the premises section. Pond data are shown in Table 5.

OIL AGGLOMERATION WITH HEPTANE RECOVERY

The process consists of four identical trains of agglomeration and heptane recovery equipment, supplied by a single feed tank and raw material storage and supply system. A flow diagram is shown in Figure 1, a material balance in Table 6, and an equipment list in Table 7. The flow diagram shows one train of the agglomeration and heptane recovery systems. The material balance and equipment list are for the entire plant.

Preceding page blank

TABLE 4. MAJOR PROCESS OPERATING CONDITIONS

	Process	
	Heptane with recovery	Fuel oil without recovery
Feedstock		
Rate, Mlb/hr	2.1	2.1
Slurry concentration, % solids	10	10
Solids composition, % by wt (dry)		
Coal	47.5	47.5
Noncoal minerals	50	50
Pyrite	2.5	2.5
Operating Conditions		
Time, hr/yr	5,500	5,500
Coal recovery, % of coal feed	92	90
Oil, % of undried product	18[a]	6.1[b]
Asphalt, % of undried product	2	0
Oil recovery, % of oil feed	97.7	0
Product[c]		
Production, ton/yr	289,000	302,000
Solids composition, % by wt (dry)		
Coal	89	83
Noncoal minerals	8	14
Sulfur	3	3
Water	<5	30
Heating value, Btu/lb (dry)	12,900	12,000
Waste		
Rate, Mlb/hr	1.9	1.9
Solids, %	5	5
Coal, % of waste	0.3	0.4

a. This number corresponds to 14.1% oil based on the weight of the feed solids and 21.4% oil based on the dry weight of the agglomerated product (water-free basis).

b. This number corresponds to 5.0% oil based on the weight of the feed solids and 8.7% oil based on the dry weight of the agglomerated product (water-free basis).

c. All product percentages and the heating values are based on the dry weight of the product (coal and all noncoal minerals, including pyrite) and do not include the weights or effects on heating value of residual oil, asphalt, or water (the heating values of the residual oil and asphalt are taken into account in the economics).

TABLE 5. POND DATA

	Holding pond	Process waste pond: Heptane with recovery	Process waste pond: Fuel oil without recovery	Hypothetical coal-cleaning plant pond
Solids, %	10	50	50	50
Total volume, kyd3	880	12,800	12,300	25,700
Capacity, yr	30[a]	30	30	30
Site area, acres	61	460	440	780
Pond area, acres	42	380	370	670
Depth, ft	14	22	22	25

a. Capacity in days.

Material Handling and Storage

A raw material storage and feed preparation area, a waste handling system, and a product handling and storage system are provided. The raw material storage and feed preparation area consists of equipment to unload and store a 30-day supply of heptane and asphalt, a storage tank for recovered heptane, metering equipment for heptane and asphalt, and the equipment (as described above) to store and prepare the feedstock. The waste handling system consists of an 8-hour-capacity storage tank and the pumps and pipelines required to pump it one mile to the disposal pond. The product storage area consists of conveyors and stacking equipment and an outdoor storage pile.

Oil-Agglomeration System

Each train of the oil-agglomeration system includes a high-shear mix tank and a low-shear mix tank. The 10% solids slurry from the feed tank is pumped to the high-shear mix tank, a vessel about 3 feet in diameter and 10 feet high with a 3-turbine agitator. Along with the slurry, 18% heptane and 2% asphalt (both based on the weight of the agglomerated product recovered from the overflow of the low-shear mix tank) are added to the tank. The average residence time in the tank is 30 seconds. The high degree of agitation produces very fine droplets of heptane (in which the asphalt is dissolved) in which the coal particles and other oleophilic minerals, mostly pyrite, agglomerate.

The liquid flows by gravity to the low-shear mix tank, which is about 13 feet in diameter and 13 feet high and has an average residence time of 10 minutes. Here a lesser degree of agitation allows the small agglomerates to coalesce into larger agglomerates 2 to 3 mm in diameter. The liquid flows from the low-shear mix tank to a vibrating screen where the

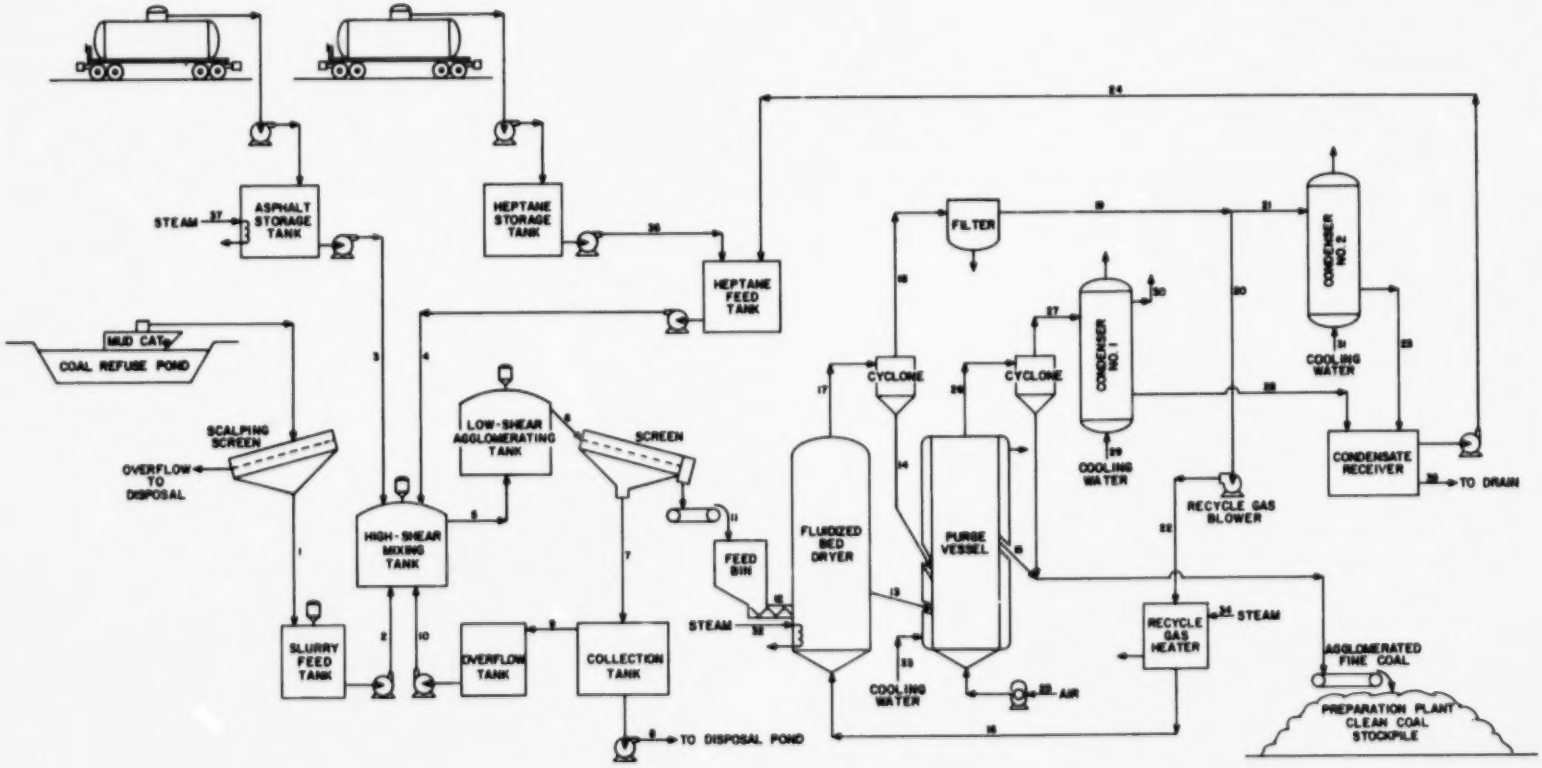

Figure 1. Oil-agglomeration process with heptane recovery.

TABLE 6. OIL-AGGLOMERATION PROCESS WITH HEPTANE RECOVERY

MATERIAL BALANCE

	Stream No.	1	2	3	4	5
	Description	Slurry from holding pond	Slurry to high shear mix tank	Asphalt to high shear mix tank	Heptane to high shear mix tank	Slurry to low shear mix tank
1	Total stream, lb/hr	2,100,000	2,100,000	3,280	29,530	2,135,960
2	Coal	99,700				
3	Noncoal minerals	105,000				
4	Pyrite	5,300				
5	Water	1,890,000				
6	Pressure, psia					
7	Gpm	4,000	4,000			4,100
8	Specific gravity	1.0	1.0			
9	Temperature, °F			400		
10	Undissolved solids, %	10	10			

	Stream No.	6	7	8	9	10
	Description	Slurry to screen	Underflow from screen	Refuse to disposal	Overflow from collection tank	Recycled overflow from collection tank
1	Total stream, lb/hr	2,135,960	1,991,900	1,968,750	23,150	23,150
2	Coal		6,500	6,200	300	
3	Noncoal minerals		101,690	96,600	5,090	
4	Pyrite		2,300	2,200	100	
5	Water		1,879,640	1,863,750	15,890	
6	Asphalt		170		170	
7	Heptane		1,600		1,600	1,600
8	Specific gravity					
9	Gpm	4,100	3,900	3,800		
10	Undissolved solids, %			5	30	30

	Stream No.	11	12	13	14	15
	Description	Agglomerated particles to feed bin	Agglomerated particles to fluidized-bed dryer	Coal agglomerates to purge vessel	Coal fines from cyclone to purge vessel	Dry coal to stockpile
1	Total stream, lb/hr	164,060	164,060	110,020	890	108,150
2	Coal	93,500				93,360
3	Noncoal minerals	8,400				8,390
4	Pyrite	3,100				3,100
5	Water	26,250				
6	Asphalt	3,280				3,280
7	Heptane	29,530				15
8	Specific gravity					
9	Temperature, °F		60	248	248	150
10	Undissolved solids, %					

	Stream No.	16	17	18	19	20
	Description	Fluidizing medium to dryer	Overhead vapor from dryer to cyclone	Vapor from cyclone to filter	Vapor from filter	Vapor to compressor
1	Total stream, lb/hr	112,950	166,990	166,100	165,950	112,950
2						
3						
4	Sft^3/min (60°F)	20,140				
5	Temperature, °F	465	248	248	248	248
6	Pressure, psia	20.7	20	19.7	19.3	19.2
7	Gpm					
8	Specific gravity					
9	pH					
10	Undissolved solids, %					

(Continued)

TABLE 6. (Continued)

	Stream No.	21	22	23	24	25
	Description	Vapor to condenser No. 2	Vapor to recycle gas heater	Condensate from condenser No. 2 to receiver	Recycled heptane to feed tank	Air to purge vessel
1	Total stream, lb/hr	53,000	112,950	53,000	28,850	63,580
2						
3						
4	Sft^3/min (60°F)					
5	Temperature, °F	248	265	100	100	60
6	Pressure, psia	15.7	23.7	14.7		
7	Gpm					
8	Specific gravity					
9	pH					
10	Undissolved solids, %					

	Stream No.	26	27	28	29	30
	Description	Gas from purge vessel to cyclone	Gas from cyclone to condenser No. 1	Condensate to receiver	Cooling water to condenser No. 1	Air from condenser No. 1 to vent
1	Total stream, lb/hr	66,340	66,340	2,500	49,820	63,840
2						
3						
4	Sft^3/min (60°F)					
5	Temperature, °F	150	150	86	60	86
6	Pressure, psia					
7	Gpm					
8	Specific gravity					
9	pH					
10	Undissolved solids, %					

	Stream No.	31	32	33	34	35
	Description	Cooling water to condenser No. 2	Steam to fluidized-bed dryer's internal heater	Cooling water to purge vessel	Steam to recycle gas heater	Water from condensate receiver to drain
1	Total stream, lb/hr	568,400	36,780	553	15,570	26,650
2						
3						
4	Sft^3/min (60°F)					
5	Temperature, °F	60	470	60	470	100
6	Pressure, psia		515		515	
7	Gpm					
8	Specific gravity					
9	pH					
10	Undissolved solids, %					

	Stream No.	36	37			
	Description	Makeup heptane to feed tank	Steam to asphalt storage tank			
1	Total stream, lb/hr	680	12,880			
2						
3						
4	Sft^3/min (60°F)					
5	Temperature, °F		470			
6	Pressure, psia		515			
7	Gpm					
8	Specific gravity					
9	pH					
10	Undissolved solids, %					

TABLE 7. EQUIPMENT LIST, OIL-AGGLOMERATION PROCESS WITH HEPTANE RECOVERY

Item: Description	Material cost, 1982$	Labor cost, 1982$
Area 1--Raw Material Handling and Feed Preparation		
1. Pump, heptane unloading (2): Centrifugal, 360 gpm, 60-ft head, 10 hp, carbon steel (1 operating, 1 spare)	7,000	1,100
2. Pump, asphalt unloading (2): Centrifugal, 1,230 gpm, 60-ft head, 40 hp, carbon steel (1 operating, 1 spare)	13,400	1,800
3. Tank, heptane storage (1): 25-ft dia x 26 ft high, 95,500 gal, carbon steel, w/cover	21,400	14,400
4. Tank, asphalt storage (1): 42-ft dia x 42 ft high, 432,300 gal, carbon steel, w/cover and 5 internal plate coils 22 in. wide x 131 in. long, 304 stainless steel	106,000	103,400
5. Pump, heptane makeup (2): Centrifugal, 2.0 gpm, 30-ft head, 1/4 hp, carbon steel (1 operating, 1 spare)	3,400	900
6. Pump, asphalt feed (6): Centrifugal, 2.5 gpm, 60-ft head, 1/4 hp, carbon steel (4 operating, 2 spares)	6,300	1,900
7. Tank, heptane feed (1): 20-ft dia x 19-1/2 ft high, 45,800 gal, carbon steel, w/cover	12,900	8,600
8. Pump, heptane feed (6): Centrifugal, 22 gpm, 30-ft head, 3/4 hp, carbon steel (4 operating, 2 spares)	10,300	2,800
9. Mud Cat (2): National Car Rental's Model No. Mc915-Ei, 41980	351,900	23,600

(Continued)

TABLE 7. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
10. Scalping screen (1): Single deck vibrating screen, mounted at 20-degree angle, 4 ft wide x 12 ft long, with deck of 3/32-in. Bixby-Zimmer Iso-rod spaced for 1/2-mm opening, 7-1/2 hp, carbon steel	10,000	600
11. Tank, slurry feed (4): 46-ft dia x 46 ft high, 571,900 gal, open top, four 46-in. baffles, agitator supports, neoprene lined, carbon steel	654,500	518,300
12. Agitator, slurry feed tank (4): 1 turbine, 184-in. dia, 75 hp, neoprene coated	322,000	23,500
13. Pump, slurry feed (6): Centrifugal, 1,073 gpm, 100-ft head, 50 hp, carbon steel, neoprene lined (4 operating, 2 spares)	44,400	13,200
Subtotal	1,563,500	714,100
Area 2--Agglomeration		
1. Tank, high-shear mixing (4): 3-ft dia x 10-1/2 ft high, 560 gal, four 3-in. baffles, agitator supports, w/cover, carbon steel, neoprene lined	46,400	32,600
2. Agitator, high-shear mix tank (4): 3 turbines, 12-in. dia., 125 hp, neoprene lined	144,000	32,300
3. Tank, low-shear mixing (4): 12-1/2-ft dia x 12-1/2 ft high, 11,500 gal, four 12-1/2-in. baffles, agitator supports, w/cover, neoprene lined, carbon steel	103,800	50,400

(Continued)

TABLE 7. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
4. Agitator, low-shear mix tank (4): 1 turbine, 50-in. dia, 125 hp, neoprene coated	120,000	25,900
Subtotal	414,200	141,200
Area 3--Agglomerates Handling		
1. Screen (4): Vibrating screen, 48 in. wide x 7 ft long, 5-degree decline, 5-hp motor, Bixby-Zimmer Iso-rod, screen deck with 1-mm opening, 1/16-in. Iso-rod, screen surface area 316 stainless steel	54,000	2,700
2. Conveyor, agglomerates feed (4): Belt, 20-1/2 ton/hr, 18-in. belt, 50 ft long, 1/2-hp motor, totally enclosed, carbon steel	80,200	8,800
Subtotal	134,200	11,500
Area 4--Waste Handling		
1. Tank, refuse collection (1): 45-1/2-ft dia x 20 ft high, 243,300 gal, open top, carbon steel, neoprene lined	71,100	56,800
2. Tank, refuse overflow (1): 14-ft dia x 20 ft high, 23,000 gal, open top, carbon steel, neoprene lined	17,100	13,400
3. Pump, refuse overflow (6): Centrifugal, 12 gpm, 100-ft head, 3/4 hp, carbon steel, neoprene lined (4 operating, 2 spares)	13,900	4,500

(Continued)

TABLE 7. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
4. Pump, refuse disposal (2): Centrifugal, 3,980 gpm, 60-ft head, 100 hp, carbon steel, neoprene lined (1 operating, 1 spare)	41,100	9,300
Subtotal	143,200	84,000
Area 5--Solvent Recovery		
1. Bin, agglomerates feed (4): 18-1/2-ft dia x 26-1/2-ft straight side, 7,100 ft3, 30-degree slope, w/cover and rotary air locks, carbon steel	94,900	76,600
2. Feeder, agglomerates feed bin (4): Screw, 12-in. dia x 16 ft long, 21 ton/hr, 3 hp, carbon steel	12,000	1,700
3. Fluidized bed dryer (4): 12 ft wide x 18 ft long, refractory lined, carbon steel, w/rotary air locks and internal heating coils	1,576,000	84,000
4. Cyclone, fluidized bed dryer (4): 7,800 aft3/min, 21 ton/hr, carbon steel, refractory lined	82,500	3,700
5. Purge vessel (4): 12-ft dia x 17 ft high, carbon steel, jacketed by a dimple jacket	96,200	6,000
6. Cyclone, purge vessel (4): 4,300 aft3/min, 8 ton/hr, carbon steel, refractory lined	66,800	5,400
7. Condenser No. 1 (4): Shell-and-tube type, 450 ft2, 316 stainless steel tubes, head, and shell	99,000	1,800
8. Condenser No. 2 (4): Shell-and-tube type, 750 ft2, 316 stainless steel tubes, head, and shell	174,000	1,900

(Continued)

TABLE 7. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
9. Heater, recycle gas (4): Steam, tube type, 272 ft^2, 316 stainless steel	86,000	1,600
10. Blower, recycle gas (6): Rotary, 125 hp, 5,300 aft^3/min, carbon steel, epoxy coated w/316 stainless steel silencers (4 operating, 2 spares)	234,000	9,300
11. Tank, condensate receiver (1): 20-ft dia x 30 ft high, 70,500 gal, w/cover, carbon steel	18,700	12,300
12. Pump, recycle heptane (3): Centrifugal, 84 gpm, 200-ft head, 7-1/2 hp, carbon steel (2 operating, 1 spare)	6,300	1,800
13. Filters (4): 345-ft^2 area, 16-in. inlet flange connection, 30-in. dia, Model CP 220-160 F1	34,600	2,100
14. Fan, air to purge vessel (6): Forced draft, 3,630 aft^3/min, 12-in. static head, 10 hp. (4 operating, 2 spares)	15,400	2,500
Subtotal	2,596,400	210,700
Area 6--Product Handling and Storage		
1. Conveyor, collecting (1): Belt, 54-1/2 ton/hr, 24-in. belt, 100 ft long, 1-hp motor, enclosed, carbon steel	18,500	1,300
2. Conveyor, transfer (1): Belt, 54-1/2 ton/hr, 24-in. belt, 250 ft long, 7-1/2-hp motor, enclosed, carbon steel	64,300	6,000

(Continued)

TABLE 7. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
3. Conveyor, stacker (1): Horizontal belt, 54-1/2 ton/hr, 30 in. wide, 500 ft long, 5-hp motor, traveling tripper, enclosed, carbon steel	202,900	25,600
Subtotal	285,700	32,900
Total	5,137,200	1,194,400

agglomerated particles are removed from the liquid and conveyed to the heptane recovery system.

The liquid that passes through the screen contains unagglomerated solids (mostly noncoal minerals) and residual heptane and asphalt. It flows to the refuse tank where the residual heptane and asphalt, along with unagglomerated coal, collect at the surface. The upper portion of liquid in the tank is recycled to the high-shear mix tank to recover these materials and the remainder is pumped one mile to the waste disposal pond.

Heptane Recovery System

Each train of the recovery system consists of a fluidized-bed dryer; a particle purge vessel; and associated gas circulating, solids collecting, and condensing equipment. The fluidized-bed dryer is a ceramic-lined vessel which has a cross-sectional area of 12 by 18 feet. It is equipped with internal steam coils that supply a portion of the heat requirement. The particles are transported from the feed bin in a screw conveyor and fed to the dryer through an air lock. The particles are fluidized with a hot vapor composed of 60% heptane and 40% water at about 6 lb/in^2 which vaporizes 95% of the heptane and water in the particles. The vapor enters at 465°F and leaves at 240°F.

The vapor from the dryer passes through a ceramic-lined cyclone and a fabric filter to remove entrained solids. Two-thirds of the vapor is passed through a compressor and heater and recycled to the dryer at 465°F. The remainder is passed through a water-cooled shell-and-tube heat exchanger in which the heptane and water are condensed and the condensate is cooled to 100°F. The condensate drains to a condensate tank in which the heptane and water separate into two phases. The heptane is returned to the agglomeration system and the water is pumped to the waste pond.

Solids from the dryer and particulate collectors flow by gravity to the purge vessel where they are purged with air at 60°F to remove the remaining heptane and water and to cool them to 150°F. The air rate is controlled to maintain the heptane concentration of the exit gas below the concentration required for combustion. The gaseous mixture of air, heptane, and water passes through a cyclone to remove entrained solids and then through a water-cooled shell-and-tube heat exchanger to condense the water and heptane, which also flow to the condensate tank. Solids from the purge vessel and the cyclone flow by gravity to a conveyor belt that transports them to the preparation plant's cleaned coal stockpile.

OIL AGGLOMERATION WITHOUT OIL RECOVERY

The nonrecovery process is based on the use of No. 2 fuel oil as the agglomerating agent. It differs from the recovery process primarily in the absence of the oil recovery system and the use of a much lower oil-to-coal ratio in order to reduce the cost. As a result of the lower oil-to-coal

ratio, the coal recovery is lower and the product particle size is smaller. Since the particles are mechanically dewatered instead of thermally dried, they also have a higher moisture content. The flow diagram is shown in Figure 2. The material balance is shown in Table 8 and the equipment list is shown in Table 9. The flow diagram shows one train of the agglomeration system. The material balance and equipment list are for the entire plant.

Material Handling and Storage

The process has similar material handling and storage areas as the recovery process. The feedstock storage and preparation, waste handling, and product storage areas are identical: the feedstock is recovered from the holding pond and pumped to the feed tank, the waste is pumped one mile to the waste disposal pond, and the product is conveyed to an outdoor storage pile. The raw material area consists of equipment to unload and store a 30-day supply of fuel oil and meter it to the agglomeration area.

Oil-Agglomeration System

The agglomeration area is identical to the agglomeration area of the recovery process. It consists of four trains, each with a high-shear mix tank and a low-shear mix tank identical in size and design to the mix tanks used in the recovery process. Only 6.1% fuel oil (based on the weight of the undried product) is used, however, as compared with 18% heptane for the recovery process. Consequently, the agglomerates produced are smaller--about 100 mesh (0.15 mm) in size--and the coal recovery rate is 2% lower. The agglomerates also contain 30% moisture, as compared with about 16% for the heptane process.

The overflow from the low-shear mix tank passes through a vibrating screen to recover the agglomerated particles which are conveyed to the product stockpile. The underflow from the vibrating screen flows to a refuse tank, from which the top portion is recycled to the high-shear mix tank to recover oil and coal that collect on the surface. The bottom portion is pumped to the waste disposal pond.

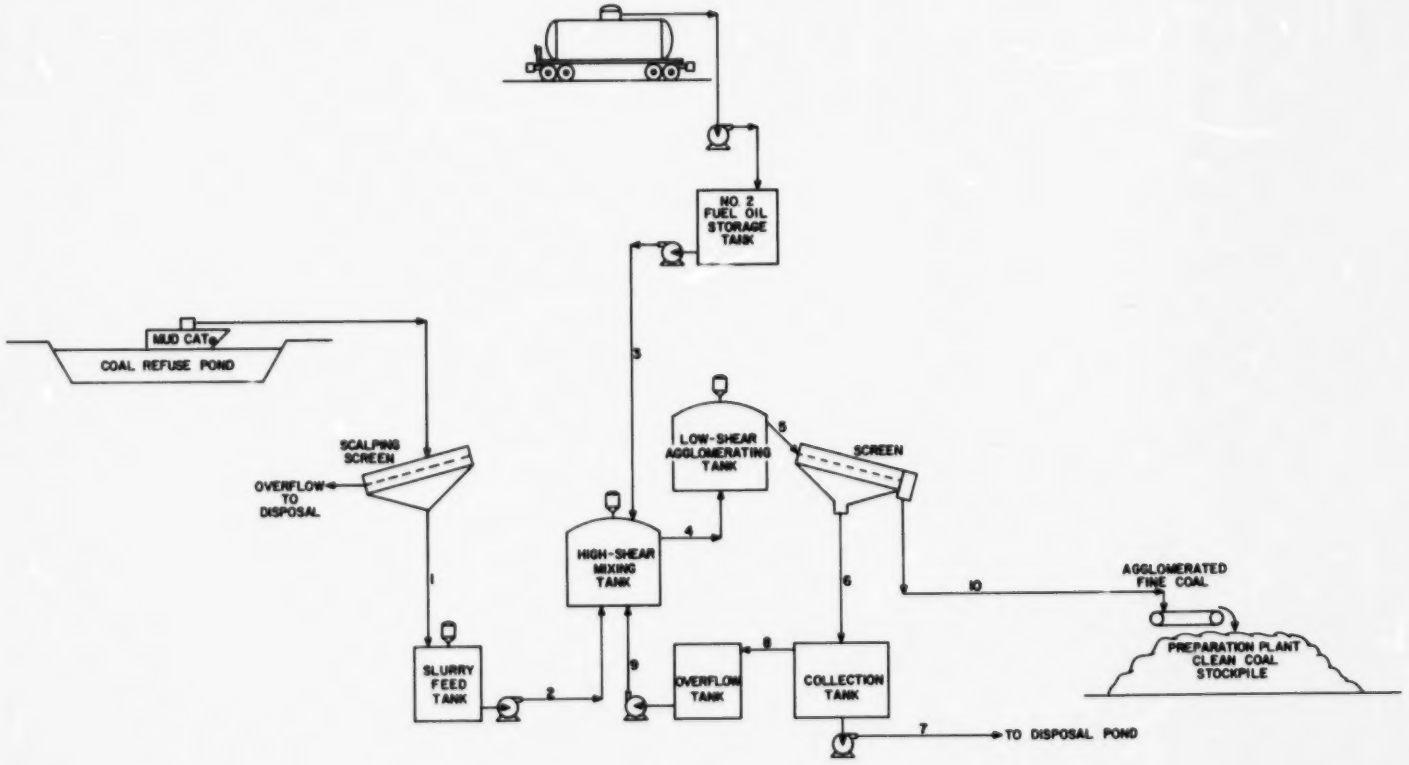

Figure 2. Oil-agglomeration nonrecovery process with fuel oil.

TABLE 8. OIL-AGGLOMERATION NONRECOVERY PROCESS WITH FUEL OIL

MATERIAL BALANCE

Stream No.		1	2	3	4	5
	Description	Slurry from holding pond	Slurry to high shear mix tank	Fuel oil to high shear mix tank	Slurry to low shear mix tank	Slurry to screen
1	Total stream, lb/hr	2,100,000	2,100,000	10,500	2,129,900	2,129,900
2	Coal	99,700				
3	Noncoal minerals	105,000				
4	Pyrite	5,300				
5	Water	1,890,000				
6	Pressure, psia					
7	Gpm	4,000	4,000		4,100	4,100
8	Specific gravity	1.0	1.0			
9	Temperature, °F					
10	Undissolved solids, %	10	10			

Stream No.		6	7	8	9	10
	Description	Underflow from screen	Refuse to disposal	Overflow from collection tank	Recycled overflow from collection tank	Coal to stockpile
1	Total stream, lb/hr	1,957,900	1,938,500	19,400	19,400	172,000
2	Coal	8,900	8,500	400		91,200
3	Noncoal minerals	94,300	89,600	4,700		15,400
4	Pyrite	2,100	2,000	100		3,300
5	Water	1,852,000	1,838,400	13,600		51,600
6	Fuel oil	600		600		10,500
7	Specific gravity					
8	Gpm	3,800	3,700			
9	Undissolved solids, %		5	30	30	
10						

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

TABLE 9. EQUIPMENT LIST, OIL-AGGLOMERATION

NONRECOVERY PROCESS WITH FUEL OIL

Item: Description	Material cost, 1982$	Labor cost, 1982$
Area 1--Raw Material Handling and Feed Preparation		
1. Pump, fuel oil unloading (2): Centrifugal, 2,200 gpm, 100-ft head, 60 hp, carbon steel (1 operating, 1 spare)	17,000	1,100
2. Tank, fuel oil storage (2): 41-ft dia x 60 ft high, 592,600 gal, carbon steel, w/cover	180,300	122,600
3. Pump, fuel oil feed (6): Centrifugal, 6-1/2 gpm, 30-ft head, 1/4 hp, carbon steel (4 operating, 2 spares)	2,900	2,300
4. Mud Cat (2): National Car Rental's Model No. Mc915-Ei, 41980	351,900	23,600
5. Scalping screen (1): Single deck vibrating screen, mounted at 20-degree angle, 4 ft wide x 12 ft long, with deck of 3/32-in. Bixby-Zimmer Iso-rod spaced for 1/2-mm opening, 7-1/2 hp, carbon steel	10,000	600
6. Tank, slurry feed (4): 46-ft dia x 46 ft high, 571,900 gal, open top, four 46-in. baffles, agitator supports, neoprene lined, carbon steel	654,500	518,300
7. Agitator, slurry feed tank (4): 1 turbine, 184-in. dia, 75 hp, neoprene coated	322,000	23,500

(Continued)

TABLE 9. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
8. Pump, slurry feed (6): Centrifugal, 1,073 gpm, 100-ft head, 50 hp, carbon steel, neoprene lined (4 operating, 2 spares)	44,400	13,200
Subtotal	1,583,000	705,200
Area 2--Agglomeration		
1. Tank, high-shear mixing (4): 3-ft dia x 10-1/2 ft high, 560 gal, four 3-in. baffles, agitator supports, w/cover, carbon steel, neoprene lined	46,400	32,600
2. Agitator, high-shear mix tank (4): 3 turbines, 12-in. dia, 125 hp, neoprene lined	144,000	32,300
3. Tank, low-shear mixing tank (4): 12-1/2-ft dia x 12-1/2 ft high, 11,500 gal, four 12-1/2-in. baffles, agitator supports, w/cover, neoprene lined, carbon steel	103,800	50,400
4. Agitator, low-shear mix tank (4): 1 turbine, 50-in. dia, 125 hp, neoprene coated	120,000	25,900
Subtotal	414,200	141,200

(Continued)

TABLE 9. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
Area 3--Agglomerates Handling		
1. Screen (4): Vibrating screen, 48 in. wide x 7 ft long, 5-degree decline, 5-hp motor, Bixby-Zimmer Iso-rod, screen deck with 100-mesh opening using 1/16-in. Iso-rod, screen surface area 316 stainless steel	55,600	2,700
Subtotal	55,600	2,700
Area 4--Waste Handling		
1. Tank, refuse collection (1): 45-ft dia x 20 ft high, 238,000 gal, open top, carbon steel, neoprene lined	70,100	56,000
2. Tank, refuse overflow (1): 13-ft dia x 20 ft high, 19,900 gal, open loop, carbon steel, neoprene lined	15,800	12,300
3. Pump, refuse overflow (6): Centrifugal, 11 gpm, 100-ft head, 3/4 hp, carbon steel, neoprene lined (4 operating, 2 spares)	12,400	4,400
4. Pump, refuse disposal (2): Centrifugal, 3,920 gpm, 60-ft head, 100 hp, carbon steel, neoprene lined (1 operating, 1 spare)	41,100	9,300
Subtotal	139,400	82,000

(Continued)

TABLE 9. (Continued)

Item: Description	Material cost, 1982$	Labor cost, 1982$
Area 5--Product Handling and Storage		
1. Conveyor, collecting (1): Belt, 86 ton/hr, 18-in. belt, 100 ft long, 1-hp motor, enclosed, carbon steel	16,500	1,300
2. Conveyor, coal transfer (1): Belt 86 ton/hr, 18-in. belt, 350 ft long, 15-hp motor, enclosed, carbon steel	88,600	8,000
3. Conveyor, stacker (1): Horizontal belt, 86 ton/hr, 24 in. wide, 500 ft long, 5-hp motor, traveling tripper, enclosed, carbon steel	182,300	24,900
Subtotal	287,400	34,200
Total	2,479,600	965,300

RESULTS

Capital investments in 1982 dollars and first-year and levelized annual revenue requirements in 1984 dollars were prepared for the recovery process using heptane and for the comparative nonrecovery process using fuel oil. Case variations for different pond credits, raw material costs, asphalt contents, and coal recoveries were evaluated for both processes. The effect of the heptane recovery rate and the type of purge gas were evaluated for the recovery process. The alternatives of using a centrifuge and of using kerosene or heptane instead of fuel oil were evaluated for the nonrecovery process.

The nonrecovery process is based on conditions typical of those conventional oil-agglomeration processes in which the quantity of oil used is minimized to reduce costs. As a result, the coal recovery rate is lower and the product is lower in quality as compared with the process with heptane recovery.

The accuracy associated with the cost estimates is minus 20% to plus 40%, based on a subjective assessment of the quantity and quality of the technical data available. However, in making comparisons between processes evaluated on the same premise basis, the accuracy is about plus or minus 10% because many possible variations affect both processes similarly.

The economics of the processes are based on the overall economic effects of recovering the coal in the coal-cleaning plant waste, which includes the costs of disposing of unprocessed waste. A pond credit is applied to account for these savings in waste disposal costs. The recovery process pond costs are shown in Table 10. The pond credits for the nonrecovery process are developed in a similar manner. The credit is the sum of the costs associated with the holding pond and waste disposal pond required when the oil-agglomeration process is used, less the costs associated with the pond that would be required for the unprocessed waste. These credits are shown separately in the economic results. The major savings are in the capital investment for pond construction, which also affect the capital charges in the annual revenue requirements. There are also small savings in pond maintenance costs.

CAPITAL INVESTMENT

The capital investments for the recovery process and the nonrecovery process with unrecovered fuel oil are shown in Tables 11 and 12. The same costs are summarized in Table 13.

TABLE 10. RECOVERY PROCESS POND COSTS AND DATA

	Capital investment, k$			
	Pond A	Pond B	Pond C	Net savings
Direct investment				
Clearing	1,524	119	898	507
Excavation	9,168	706	5,372	3,090
Dike construction	4,952	408	2,923	1,621
Lining	2,721	170	1,557	994
Road, fence, wells	414	118	318	(22)
Reclamation	3,128	246	1,851	1,031
Tax and freight	17	4	11	2
Total direct	21,924	1,771	12,930	7,223
Indirect investment	6,051	489	3,568	1,994
Other capital investment	8,918	711	5,256	2,951
Total capital investment	36,893	2,971	21,754	12,168

Pond A: 30-year disposal pond for the unprocessed coal-cleaning plant waste.

Pond B: 30-day holding pond for the coal-cleaning plant waste feedstock.

Pond C: 30-year disposal pond for the oil-agglomeration plant waste.

At the specified conditions, the capital investment for the nonrecovery process which is about $13 million without the pond credit is substantially lower in cost than the recovery process which has a capital investment of about $21 million. As shown in Table 13, the only significant difference in capital investment between the recovery process and the nonrecovery process is the cost of the recovery system, which accounts for 43% of the process capital. From an economic standpoint, this system is essentially an independent component and has very little effect on other capital investment costs. The only effects are a slight increase in the agglomerates handling area costs because of the conveyors used to transport the coal agglomerates to the recovery system, and a slight decrease in the

TABLE 11. OIL-AGGLOMERATION PROCESS WITH HEPTANE RECOVERY

CAPITAL INVESTMENT

	Capital investment, k$		
	Process	Pond credit	Net
Direct investment			
Material handling and feed preparation	3,380		
Agglomeration	907		
Agglomerates handling	355		
Waste handling	640		
Heptane recovery	4,275		
Product handling and storage	458		
Total process capital	10,015		
Services, utilities, and miscellaneous	601		
Total direct investment	10,616	(7,223)	3,393
Indirect investment			
Engineering design and supervision	743		
Architect and engineering contractor	212		
Construction expense	1,699		
Contractor fees	531		
Contingency	2,760		
Total fixed investment	16,561	(9,217)	7,344
Other capital charges			
Allowance for startup and modifications	1,325		
Interest during construction	2,584		
Royalties	100		
Land	20		
Working capital	909		
Total capital investment	21,499	(12,168)	9,331

Basis: North-central plant location, plant sized to process 2.1 million ton/yr of 10% solids coal-cleaning plant waste, operating 5,500 hr/yr for 30 years and producing 289,000 ton/yr of 12,900 Btu/lb (less asphalt and oil credit) recovered coal. 1981 to 1983 construction period, 1982 cost basis.

TABLE 12. OIL-AGGLOMERATION NONRECOVERY PROCESS WITH FUEL OIL

CAPITAL INVESTMENT

	Capital investment, k$		
	Process	Pond credit	Net
Direct investment			
Material handling and feed preparation	3,428		
Agglomeration	907		
Agglomerates handling	250		
Waste handling	623		
Product handling and storage	460		
Total process capital	5,668		
Services, utilities, and miscellaneous	340		
Total direct investment	6,008	(7,670)	(1,662)
Indirect investment			
Engineering design and supervision	421		
Architect and engineering contractor	120		
Construction expense	961		
Contractor fees	300		
Contingency	1,562		
Total fixed investment	9,372	(9,786)	(414)
Other capital charges			
Allowance for startup and modifications	750		
Interest during construction	1,462		
Royalties	57		
Land	10		
Working capital	1,109		
Total capital investment	12,760	(12,926)	(166)

Basis: North-central plant location, plant sized to process 2.1 million ton/yr of 10% solids coal-cleaning plant waste, operating 5,500 hr/yr for 30 years and producing 302,000 ton/yr of 12,000 Btu/lb (less oil credit) recovered coal. 1981 to 1983 construction period, 1982 cost basis.

material handling and feed preparation area costs because of the smaller storage requirements for the makeup and recovered heptane than the storage requirements for the fuel oil with the nonrecovery process.

TABLE 13. SUMMARY OF CAPITAL INVESTMENTS

Investment area	Capital investment, k$	
	Recovery process	Nonrecovery process
Direct investment		
Material handling and feed preparation	3,380	3,428
Agglomeration	907	907
Agglomerates handling	355	250
Waste handling	640	623
Heptane recovery	4,275	-
Product handling and storage	458	460
Total process capital	10,015	5,668
Other capital costs	11,484	7,092
Total capital investment excluding pond credit	21,499	12,760
Pond credit	(12,168)	(12,926)
Total capital investment	9,331	(166)

Aside from the heptane recovery system, the material handling and feed preparation area is the only area with large direct investment costs. Most of the costs in this area involve recovery of the feedstock from the pond and holding it in the feed tank. The large volume of low-solids slurry requires expensive dredges and a large-volume pumping and storage system (see the equipment costs listed in the equipment lists). The agglomerating process itself, with short hold times and simple equipment,

is relatively inexpensive; the agglomerates handling system is also quite simple and low in cost because of the small quantity of product (roughly equivalent to the coal feed rate of a 100-MW boiler). The waste disposal costs are also low (excluding pond costs) because wastes are pumped directly to a pond.

The pond credit has a very large effect on the capital investment, reducing the overall costs of the recovery system from $21 million to $9 million, and of the nonrecovery systems from $13 million to a capital investment credit of $0.2 million. The difference is illustrative of the large costs associated with pond disposal of large volumes of wastes.

ANNUAL REVENUE REQUIREMENTS

The annual revenue requirements for the recovery process and nonrecovery process with fuel oil are shown in Tables 14 and 15. A summary of the annual revenue requirements for these processes is shown in Table 16. The values in Table 16 include the pond credit in all cases. (In annual revenue requirements, the pond credit is reflected in lower capital charges and in a small maintenance cost credit; other costs are unaffected.)

The recovery process has first-year annual revenue requirements of $6.4 million, as compared with $8.0 million for the nonrecovery process with fuel oil, including the pond credit in both cases. The levelized annual revenue requirements are appreciably higher--$10.8 million for the recovery process and $15.1 million for the nonrecovery process, also including the pond credit. The larger than normal difference between first-year and levelized annual revenue requirements is a result of the high ratio of operating and maintenance costs to capital charges, particularly when the pond credit is applied to the capital investment. (For most coal-cleaning processes, the capital charges are roughly one-half of the annual revenue requirements.) When the pond credit is included, the capital charges for the recovery process are only 21% of the first-year annual revenue requirements and a small credit is received for the nonrecovery process. Without the pond credit, the capital charges for the recovery and nonrecovery processes are about 37% and 18% of the first-year annual revenue requirements, respectively, still reflecting relatively low capital, high operating cost processes.

The first-year annual revenue requirements expressed in unit costs are 0.86 $/MBtu (22 $/ton) for the recovery process and 1.10 $/MBtu (27 $/ton) for the nonrecovery process, including the pond credit in both cases. Without the pond credit, the unit costs are 1.15 $/MBtu (30 $/ton) for the recovery process and 1.42 $/MBtu (34 $/ton) for the nonrecovery process. These compare quite favorably with the costs of eastern bituminous coals: an eastern bituminous coal with a heating value of 11,000 Btu/lb and costing 40.70 $/ton has an equivalent cost of 1.85 $/MBtu (7).

The sources of the difference in annual revenue requirements between the recovery and nonrecovery processes are evident in a line-by-line

TABLE 14. OIL-AGGLOMERATION PROCESS WITH HEPTANE RECOVERY

ANNUAL REVENUE REQUIREMENTS

	Annual quantity	Unit cost, $	Total annual cost, k$ Process	With pond credit
Direct costs--first year				
Raw materials				
Heptane	660,400 gal	1.60/gal	1,057	1,057
Asphalt	9,024 ton	189.20/ton	1,707	1,707
Total raw material cost			2,764	2,764
Conversion costs				
Operating labor and supervision	27,500 man-hr	15.00/man-hr	413	413
Utilities				
Fuel	88,000/gal	1.60/gal	141	141
Process water	408,000/kgal	0.14/kgal	57	57
Electricity	10,405,000 kWh	0.037/kWh	385	385
Steam	358,750 klb	2.50/klb	897	897
Maintenance (labor and material)				
Process			637	637
Pond			-	(217)
Analysis	2,080/man-hr	21.00/man-hr	44	44
Total conversion costs			2,574	2,357
Total direct costs			5,338	5,121
Indirect costs--first year				
Overheads				
Plant and administrative (60% conversion cost less utilities)			656	526
Heptane heat credit	1,680 MBtu	1.85/MBtu	(3)	(3)
Asphalt heat credit	334,600 MBtu	1.85/MBtu	(619)	(619)
Total first-year operating and maintenance costs			5,372	5,025
Levelized capital charges (14.7% of total capital investment)			3,160	1,372
Total first-year annual revenue requirements			8,532	6,397
Levelized first-year operating and maintenance cost (1.886 first-year O&M)			10,132	9,477
Levelized capital charges (14.7% of total capital investment)			3,160	1,372
Levelized annual revenue requirements			13,292	10,849

	Process		With pond credit	
	$/ton recovered dry coal	$/MBtu recovered coal	$/ton recovered dry coal	$/MBtu recovered coal
First-year annual revenue requirements	30	1.15	22	0.86
Levelized annual revenue requirements	46	1.79	38	1.46

Basis: 1984 dollars. One-year 5,500-hr/yr operation of plant described in capital investment table.

TABLE 15. OIL-AGGLOMERATION NONRECOVERY PROCESS WITH FUEL OIL

ANNUAL REVENUE REQUIREMENTS

	Annual quantity	Unit cost, $	Total annual cost, k$ Process	With pond credit
Direct costs--first year				
Raw materials				
Fuel oil	8,052,000 gal	1.09/gal	8,777	8,777
Total raw material cost			8,777	8,777
Conversion costs				
Operating labor and supervision	22,000 man-hr	15.00/man-hr	330	330
Utilities				
Fuel	88,000/gal	1.60/gal	141	141
Process water			0	0
Electricity	7,230,000 kWh	0.037/kWh	268	268
Maintenance (labor and material)				
Process			360	360
Pond			-	(230)
Analysis	2,080/man-hr	21.00/man-hr	44	44
Total conversion costs			1,143	913
Total direct costs			9,920	9,690
Indirect costs--first year				
Overheads				
Plant and administrative (60% conversion cost less utilities)			440	302
Fuel oil heat credit	1,057,000 MBtu	1.85/MBtu	(1,955)	(1,955)
Total first-year operating and maintenance costs			8,405	8,037
Levelized capital charges (14.7% of total capital investment)			1,876	(24)
Total first-year annual revenue requirements			10,281	8,013
Levelized first-year operating and maintenance cost (1.886 first-year O&M)			15,852	15,157
Levelized capital charges (14.7% of total capital investment)			1,876	(24)
Levelized annual revenue requirements			17,728	15,133

	Process		With pond credit	
	$/ton recovered dry coal	$/MBtu recovered coal	$/ton recovered dry coal	$/MBtu recovered coal
First-year annual revenue requirements	34	1.42	27	1.10
Levelized annual revenue requirements	59	2.44	50	2.09

Basis: 1984 dollars. One-year 5,500-hr/yr operation of plant described in capital investment table.

TABLE 16. SUMMARY OF ANNUAL REVENUE REQUIREMENTS

	Annual revenue requirements, k$	
	Recovery process	Nonrecovery process
Raw materials		
Oil	1,057	8,777
Asphalt	1,707	0
	2,764	8,777
Conversion costs		
Labor and supervision	413	330
Utilities		
Fuel	141	141
Process water	57	0
Electricity	385	268
Steam	897	0
Maintenance	420	130
Analysis	44	44
Conversion costs	2,357	913
Direct costs	5,121	9,690
Overheads	526	302
Heat credit	(622)	(1,955)
Operating and maintenance costs	5,025	8,037
Capital charges	1,372	(24)
First-year annual revenue requirements	6,397	8,013
[$/MBtu]	[0.86]	[1.10]
[$/ton]	[22]	[27]
Levelized annual revenue requirements	10,849	15,133
[$/MBtu]	[1.46]	[2.09]
[$/ton]	[38]	[50]

comparison of the cost breakdowns in Table 16. In every category except the oil cost and the heat credit, the costs are higher for the recovery process.

The raw material costs for the recovery process (with pond credit) are 69% lower than for the nonrecovery process. These lower costs have a major effect on the economics because raw material costs are the dominant cost element in both processes--43% of the first-year annual revenue requirements for the recovery process and over 100% for the nonrecovery process.

The recovery process has conversion costs (labor, utilities, maintenance and analysis, including a small credit for pond maintenance) 2.6 times higher than the nonrecovery process. Without the pond maintenance credit, the recovery process conversion costs are 2.3 times higher. Almost all of the higher conversion costs are related to the recovery system, particularly steam costs, which are negligible for the nonrecovery process but are 35% of the conversion costs of the recovery process. However, most of the other conversion costs for the recovery process are substantially higher (labor 25%, electricity 44%, and maintenance 223%).

CASE VARIATIONS

Case variations in which one variable is changed from the base case are shown in Table 17 for different pond credits, raw material costs, asphalt contents, and coal recoveries for the recovery process and the nonrecovery process with fuel oil. Different heptane recoveries and purge gases are also shown for the recovery process, along with the effects of including a pelletizing system for the product. The alternatives of using a centrifuge to dewater the coal agglomerates to 12% moisture and of using kerosene or heptane instead of fuel oil are also shown for the nonrecovery process.

The pond credit has a major effect on both the capital investment and annual revenue requirements of both processes. With the pond credit, the capital investment for the recovery process is decreased 57% and the annual revenue requirements are decreased 25%. With the pond credit, the capital investment for the nonrecovery process is decreased over 100% and the annual revenue requirements are decreased 23%. The recovery process has a smaller pond credit because it produces more waste, but the relative difference in pond credit between the two processes is small compared with the relative difference in other costs.

The cost of the oil (agglomerating agent) used in the nonrecovery process has a major effect on its annual revenue requirements. In comparison to No. 2 fuel oil at 1.09 $/gal, the use of kerosene at 1.32 $/gal and heptane at 1.60 $/gal increased the annual revenue requirements by 32% and 92%, respectively. The other differences in heat credit and in working capital, which is reflected in capital charges, are also considered to be significant factors but are small compared with the raw material cost.

TABLE 17. CASE VARIATION COST SENSITIVITIES

Variation	Oil agglomeration with heptane recovery				Oil agglomeration with fuel oil			
	Capital investments[a]		Annual revenue requirements[a,b]		Capital investments[a]		Annual revenue requirements[a,b]	
	M$	Change, %	$/MBtu	Change, %	M$	Change, %	$/MBtu	Change, %
Pond credit								
Base case	9.3		0.86		(0.2)		1.10	
50% of base case	15.4	+66	1.00	+16	6.3	+3,250	1.26	+15
No pond credit	21.5	+131	1.15	+34	12.8	+6,500	1.42	+29
Raw materials price[c]								
80% of base case	9.29	-0.1	0.79	-8	(0.3)	-50	0.86	-22
Base case	9.3		0.86		(0.2)		1.10	
140% of base case	9.4	+1	1.01	+17	0.1	+150	1.60	+45
Asphalt used[d]								
50% of base case	9.1	-2	0.78	-9				
Base case	9.3		0.86		(0.2)		1.10	
150% of base case	9.6	+3	0.94	+9	1.0	+600	1.41	+28
Coal recovery[e]								
90% of base case	9.5	+2	0.95	+10	1.5	+850	1.27	+15
Base case	9.3		0.86		(0.2)		1.10	
105% of base case	9.1	-2	0.82	-5	(1.2)	-500	1.02	-7
Heptane recovery								
80%	10.0	+8	1.96	+128				
90%	9.6	+3	1.34	+56				
95%	9.4	+1	1.03	+20				
Base case (97.7%)	9.3		0.86					
99.7%	9.2	-1	0.74	-14				
Purge gas								
Base case (air)	9.3		0.86					
Inert gas	9.2	-1	0.74	-14				
Nitrogen	9.8	+5	0.75	-13				
Pelletization								
Base case	9.3		0.86					
Base case with pelletization	10.5	+13	1.06	+23				
Centrifuge								
Base case					(0.2)		1.10	
Base case with centrifuge					0.1	+150	1.21	+10
Oils								
Base case (fuel oil)					(0.2)		1.10	
Kerosene					0.1	+150	1.45	+32
Heptane					0.5	+350	2.11	+92

a. 1982 dollars.
b. First-year annual revenue requirements in 1984 dollars.
c. Asphalt and heptane or fuel oil.
d. 1%, 2%, and 3% of undried product for the recovery process; 0% and 3% for the nonrecovery process.
e. 83%, 92%, and 97% for the recovery process; 81%, 90%, and 95% for the nonrecovery process.

EFFECT OF OIL CONSUMPTION ON ANNUAL REVENUE REQUIREMENTS

The effects of the quantity of oil used on the costs of the nonrecovery processes are shown in Table 18, which shows the costs for oil contents in the agglomerated coal of 1.3%, 6.1% (the base case conditions), and 18%, based on the agglomerated product from the screen. The same data are shown graphically in Figure 3 with the pond credit and Figure 4 without the pond credit in comparison with the recovery process at different oil recovery efficiencies. The recovery process has the same oil and asphalt contents in the agglomerated coal as the maximum level used for the nonrecovery processes--18% oil and 2% asphalt.

The nonrecovery processes' annual revenue requirements increase rapidly with increasing oil consumptions. At oil levels greater than 11% of the agglomerated coal, the cost of the product with the pond credit exceeds the cost of the premise coal at 1.85 $/MBtu; therefore, the nonrecovery process is not economically competitive at those levels.

The recovery process's annual revenue requirements are not directly related to the oil content in the agglomerated coal, but rather to the efficiency of the oil recovery system. At high oil recovery rates (for example, the 97.7% efficiency, 2.3% oil loss, used for the base case), the recovery process is economically competitive with the nonrecovery process operating with low oil levels. The first-year annual revenue requirements for the nonrecovery process at the lower oil contents in the agglomerated coal (4.5% or less) are lower than for the recovery process, but a poorer quality of product (lower heating value, smaller particle size, and higher moisture content) is produced. If the quality of the product produced using the lower oil-to-coal ratios is acceptable, then the nonrecovery process is more economical. If the process requires a higher oil content in the agglomerated coal (e.g., in this study more than 4.5% fuel oil, which is less than the 6.1% used for the base case) to produce an adequate product, the agglomeration process with a recovery system may be the most economical method for recovering fine coal from coal preparation plant refuse. However, as the recovery efficiency decreases (percent oil loss increases), the annual revenue requirements increase rapidly as shown in Figure 3. If the recovery system efficiency is less than 93% (7% or higher oil loss), the base case nonrecovery process will be the most economical method. At an 18% to 20% oil loss in the recovery process, the cost of the product with the pond credit exceeds that of the premise coal at 1.85 $/MBtu.

TABLE 18. EFFECT OF OIL CONSUMPTION ON NONRECOVERY PROCESS COSTS

	Low range fuel oil level	Base case	Maximum fuel oil level
Operating conditions			
Oil, % of undried product	1.3	6.1	18.0
Product[a]			
Production, ton/yr	275,300	302,000	289,000
Coal, %	86	86	92
Noncoal minerals, %	14	14	8
Water, %	50	30	16
Heating value, Btu/lb	12,000	12,000	12,900
Pond credit, M$	11.42	12.93	12.17
Capital investment, M$[b]	(0.1)	(0.2)	2.49
Annual revenue requirements, k$[b]			
Oil	2,158	8,777	25,269
Conversion costs	1,143	1,215	1,431
Heat credit	(499)	(1,955)	(5,488)
Capital charges	(14)	(24)	366
Total	2,887	8,013	21,578
$/MBtu[a]	0.44	1.10	2.90
$/ton[a]	10	27	75

a. All values are based on dry product excluding oil and asphalt.
b. With pond credit.

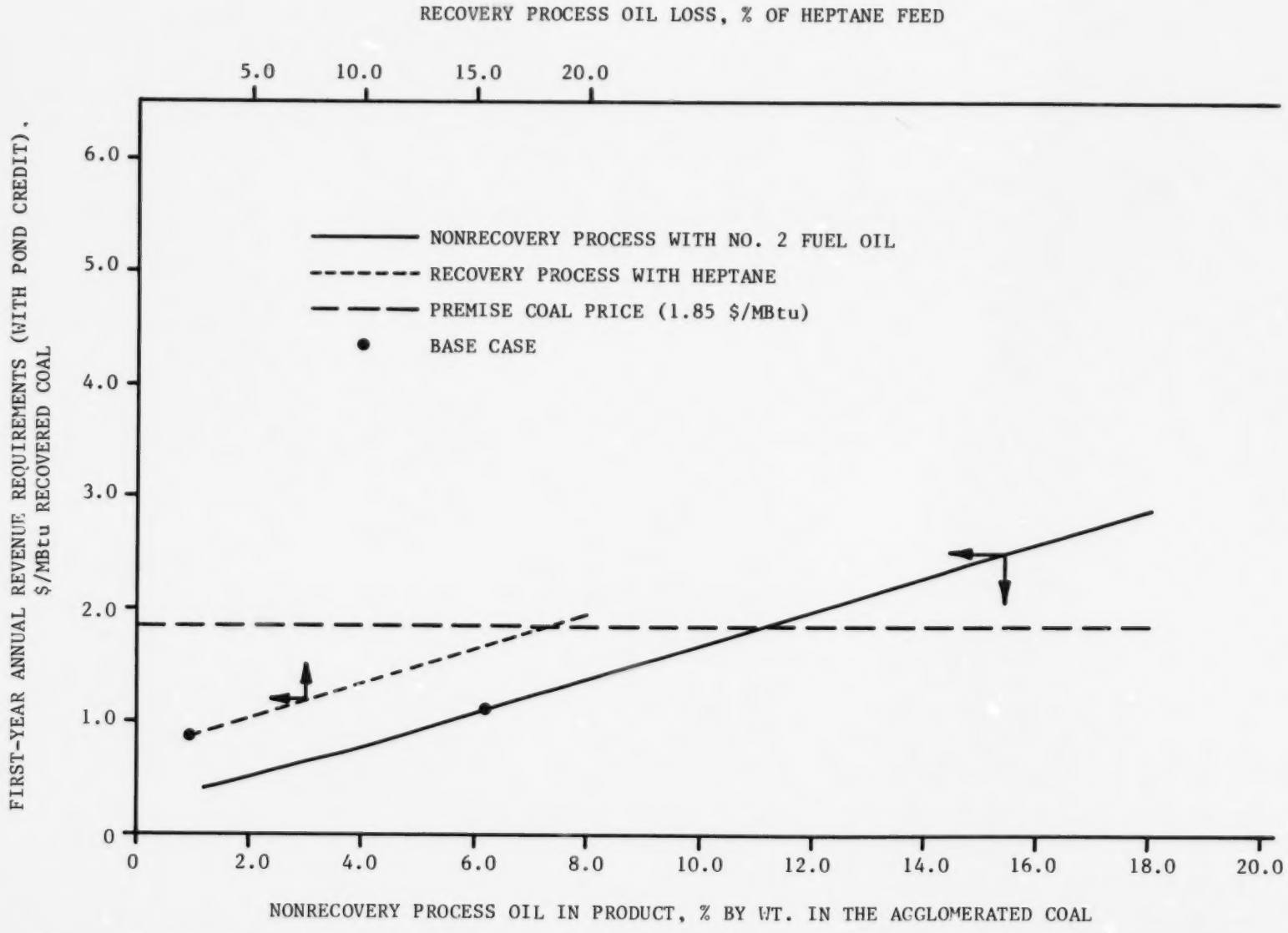

Figure 3. First-year annual revenue requirements (with pond credit) for the recovery and nonrecovery processes.

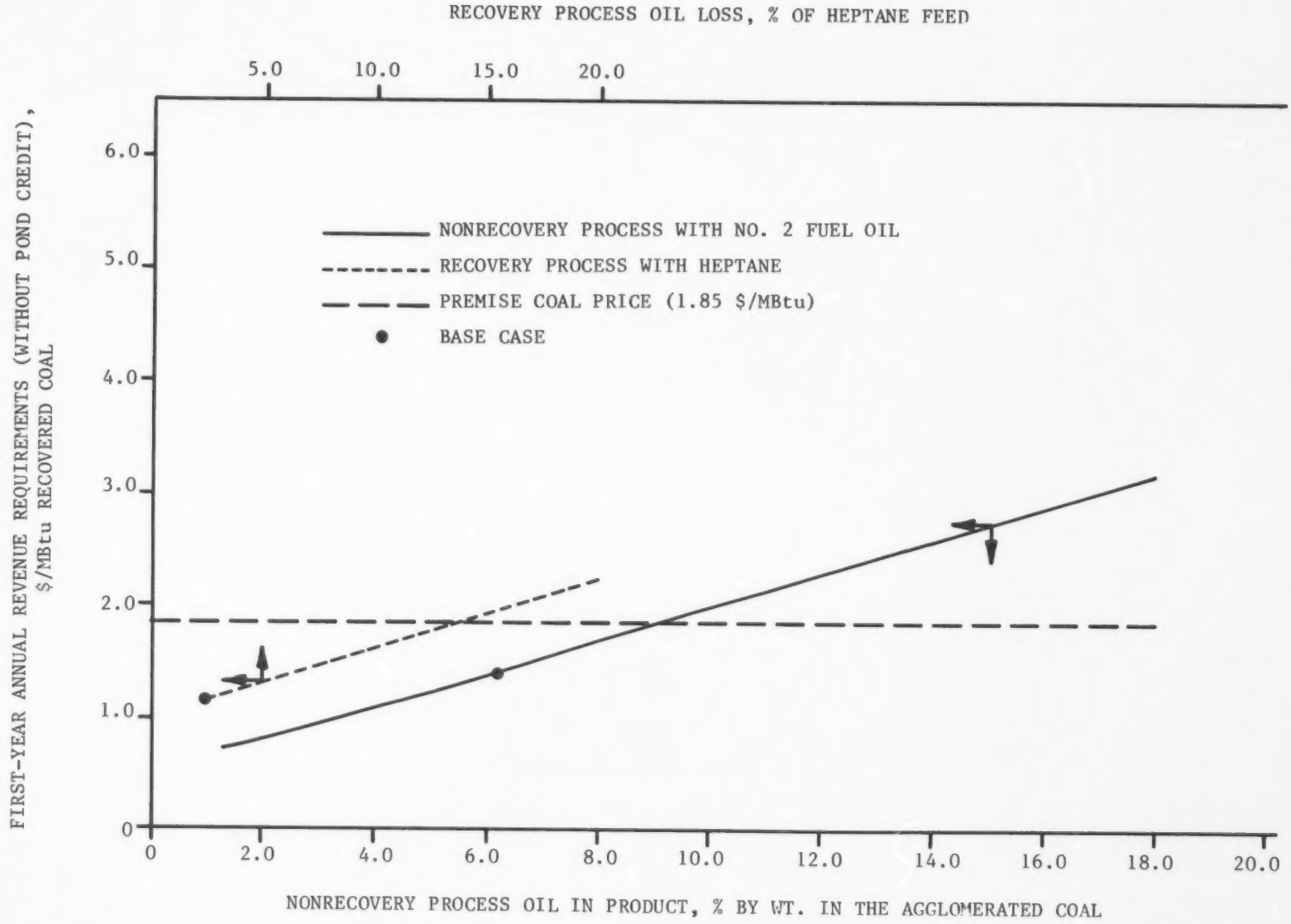

Figure 4. First-year annual revenue requirements (without pond credit) for the recovery and nonrecovery processes.

CONCLUSIONS

Both the recovery and nonrecovery oil-agglomeration processes appear to be economically feasible methods of recovering fine coal from coal-cleaning plant refuse. The value of the product in terms of heat content is economically competitive with typical eastern bituminous coals under a range of conditions typical of those used in this study. The recovery process provides a greater degree of flexibility in that the economics are less sensitive to the quantity of oil used for agglomeration, allowing the production of a higher quality product than is economically feasible with the nonrecovery processes.

The base case recovery process is less expensive than the base case nonrecovery process because of the high costs of the oil loss in the nonrecovery system. [The raw material cost for the nonrecovery process is over 100% of the total first-year annual revenue requirements ($8.8 million versus $8.0 million).] The recovery process is also capable of producing a product with less than 1% moisture content; whereas, the product in the nonrecovery process contains 30% moisture.

The elimination of the capital investment for a coal-cleaning plant waste disposal pond is an important economic factor in the use of an oil-agglomeration process. The reduction in waste volume results in a reduction in pond capital investment equal to 57% of the process capital investment of the recovery process and over 100% of the process capital investment of the fuel oil nonrecovery process. The resulting lower capital charges and maintenance costs reduce the annual revenue requirements of the recovery process by 25% and of the fuel oil nonrecovery process by 22%.

From the standpoint of capital investment, the heptane recovery system is essentially a separate system with little effect on other process capital investment. The recovery system increases the direct process costs by three-fourths and is the only major difference in process capital investment between the recovery and nonrecovery processes.

Excluding the heptane recovery system, the major capital investment costs for both processes are for feedstock handling (dredging and tank storage); over one-half of the process capital investment for both processes is for feedstock handling. Different methods of supplying the feedstock to the agglomeration system would thus have important economical effects on the processes. The method used in this study--a 30-day holding pond and an 8-hour feed tank--isolates the oil-agglomeration system from the operation of the coal-cleaning plant, and to a lesser extent from the hour-by-hour operation of the recovery dredges, though at a substantial increase in capital investment.

Preceding page blank

The annual revenue requirements of both processes are dominated by the raw material costs which constitute (for the cases with pond credits) over 40% of the recovery process annual revenue requirements and over 100% of the nonrecovery process annual revenue requirements. As a result of the importance of raw material costs, the economics of the nonrecovery process are essentially dependent on the price and the quantity of the oil used and those of the recovery process on the price of asphalt and the oil recovery efficiency.

The conversion costs are substantially higher for the recovery process. Most of the increase is a result of the steam costs which account for 38% of the conversion costs and 14% of the first-year annual revenue requirements of the recovery process. However, the steam requirements for the recovery process may be reduced by operating the fluidized-bed dryer at a lower temperature. In this study, the dryer was assumed to be operated at 248°F, but more recent data have shown that the dryer may be operated at a temperature of approximately 198°F.

The economics of the recovery process at intermediate oil levels were not assessed because of the lack of comprehensive technical data on the properties of the product. It is evident, however, that intermediate oil levels (and the corresponding lower asphalt consumption) would not have a major effect on the capital investment of the oil recovery system because the major equipment requirements are largely determined by the solids rate rather than the oil rate. In addition, operating costs would be increased, particularly by the higher steam requirements for evaporating the additional water in the product. In general, the use of an oil recovery system appears to favor a concomitant operation at conditions that produce a high coal recovery rate and a high quality product.

As a result of the more favorable economics for the recovery process at the higher oil recovery efficiencies (greater than 93%), it is recommended that this technology be tested to determine if the recovery system can be operated with the desired efficiency. If the recovery system cannot operate at the higher recovery efficiencies, then examination of the nonrecovery process may be advisable.

REFERENCES

1. Capes, C. E., et al., "Agglomeration in Coal Preparation." Paper presented at 12th Biennial Conference. The Institute for Briquetting and Agglomeration, August 1971.

2. Thomas, W. A., "Arcanum Coal Recovery Project Funds Justification Background for Contract Purposes," Memorandum, J03-810316-350, March 1981.

3. Wheelock, T. D., Coal Desulfurization Chemical and Physical Methods, ACS Symposium Series 64, 1977, pp. 48-50.

4. Private Communication, Stern, Helmut F., and J. A. Getsoian, Arcanum Corporation.

5. Fluid Bed Demonstration Unit for Solvent Recovery from Coal Agglomerates, Proposal to Arcanum Corporation, Davy McKee Engineers and Constructors, April 1982.

6. Capes, C. E., and Y. V. Nuygen, "Coal Recovery from Coal Preparation Plant Refuse Streams by Oil Agglomeration Process," memorandums, May 1984.

7. Kaplan, S., 1983, Fuel-Grade Coke Could Gain Status as Product, Oil and Gas Journal, Volume 8, No. 41, October 10, pp. 95-98.